THERMAL LOADS AND THRESHOLD CRITERIA FOR ACCEPTORS IN THE HIGH PERFORMANCE MAGAZINE

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ABSTRACT

The paper presents the results of an analytical and numerical investigation of the High Performance (HP) Magazine for thermal cookoff hazards and mitigation. The HP Magazine consists of an earth-covered box structure enclosing a vehicle accessible shipping and receiving area and two storage wings. Each storage wing is divided by relocatable walls into covered stor▾age cells which can contain up to 30,000 lbs net explosive weight of palletized or containerized munitions. Thermal cookoff threshold models have been developed for three (out of eight) HP Magazine Storage Compatibility Group categories of munitions considered most hazardous with respect to cookoff that could be stored in the magazine (explosives and flammable liquids, bombs, and solid propellant missiles). Gas temperature histories within the magazine have been predicted for fires involving worst case donors. These temperatures were then used to predict subsequent reactions of other munitions stored in storage cells. Total energy release predictions were based on a fire consuming an established amount of energetic material in either the shipping and receiving area or in a storage cell over a 30-minute period. The gas temperature histories were used in conjunction with the munition cookoff models to predict responses. The results indicated that the Bombs category was the most sensitive to thermal hazard. Mitigation techniques were explored to prevent cookoff of the stored munitions.

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NOMENCLATURE

Variables

Symbol / Description / (Units)

A_f	area of floor surface (ft^2)
A^*	area of ventilation (ft^2)
C	constant
c_p	heat capacity (Btu/lb-°R)
E	activation energy (Btu/mole)
G	thermal conductance (Btu/sec-°F)
g	gravitational acceleration (ft/sec^2)
$\dot{H}$	total enthalpy rate (Btu/sec)
i, j	node designators
k	thermal conductivity (Btu/sec-in-°R)
L	characteristic length (feet)
$\dot{m}$	mass flowrate (lb_m/sec)
P	pressure (lb_f/ft^2)
Q	heat of reaction (cal/gm)
$\dot{Q}$	heat transfer rate (Btu/sec)
q	internal heat generation (Btu/sec)
R	universal gas constant (Btu/mole-°R)
r	radius of munition (inch)
T	temperature
t	time (sec, min, hr)
V	volume (ft^3)
Z	collision frequency(sec^{-1})
z	axial distance of munition (inch) or vertical height (feet)
β	gas expansion coefficient (1/°R)
γ	ratio of specific heats
μ	viscosity (lb_m/ft-sec)
θ	angle (degrees)
ρ	density (lb_m/ft^3, lb_m/in^3)

Subscripts

c	ceiling
e	ventilation
L	lower layer
U	upper layer

Operators

e	exponential (natural)
log	natural logarithm
$\sqrt{}$	square root
Δ	difference operator
∇^2	Lapacian operator
∂	partial differential

NOMENCLATURE

ABBREVIATION LIST

Btu	British Thermal Units
CA	California
cal	calories
CBC	chemically bonded ceramic
CFAST	Consolidated Fire & Smoke Transport
CFD	computational fuid dynamics
EM	Energetic Materials
°F	degrees Fahrenheit
ft	foot or feet
gm	gram
GP	general purpose
HE	high explosive
HP	High Performance
hr	hour
J	Joule
kcal	kilocalorie
kg	kilogram
lb	pounds (mass)
m	meter
MCE	Maximum Credible Event
min	minute
Mk	Mark
NAWCWPNS	Naval Air Warfare Center - Weapons Division
NEW	Net Explosive Weight
NFESC	Naval Facilities Engineering Service Center
NIST	National Institute of Standards and Technology
NSWC	Naval Surface Warfare Center
PNR	Point-of-No Return (duration after which thermal cookoff is inevitable)
°R	degrees Rankin
sec or s	seconds
SCG	Storage Comptibility Group
SINDA	System Improved Numerical Differencing Analyzer
SRA	Shipping & Receiving Area
TNT	tri-nitrotoulene
TPM	Thermal Protection Material

INTRODUCTION

The Waterfront Structures Division (Code ESC 62) of the Naval Facilities Engineering Service Center (formerly the Naval Civil Engineering Laboratory) at Port Hueneme, CA has engaged in a project to develop a new ordnance storage magazine designed to allow safe storage of Class/Division 1.1 (mass detonating) Navy and Marine Corps ordnance, signicantly reduce the encumbered land area, and improve the efciency of weapons handling operations. The most important performance criteria for this new High Performance (HP) Magazine is reduction in the Maximum Credible Event (MCE) to 30,000 pounds (lb) Net Explosive Weight (NEW) of High Explosive (HE) in any storage cell and up to 55,000 lb NEW in the Shipping and Receiving Area (SRA). An MCE is the largest single mass detonation of a stack of munitions that can be expected. The HP Magazine design includes provisions for rapid reconguration to accommodate storage of a wide variety of ordnance categories.

The HP Magazine consists of a rectangular concrete box incorporating a vehicle parking and loading / staging dock in the SRA, anked on either side by storage bays each divided into two pits separated by relocatable, non-propogation walls and covered with sliding panels. The entrance includes a vehicle portal and personnel passageway. Overhead bridge cranes will perform Ordnance handling. The structure is to be covered with soil to limit the safe distance from blast and debris hazards. Ventilation requirements remain to be determined, and will be inuenced by the results from this report.

The Thermal Analysis Branch (Code C2893) of the Naval Air Warfare CenterWeapons Division (NAWCWPNS) has been tasked through the Ordnance Evaluation Branch (Code C2769), also of NAWCWPNS, with assessment of the thermal cookoff hazards of ordnance stored in the HP Magazine from are hazard scenario. The fundamental question addressed in this report is whether an event (re) in the HP Magazine can lead to a MCE of greater than 10,000 lb NEW in any single storage cell or 55,000 lb NEW in the SRA, and if so, what mitigation techniques should be incorporated to prevent this occurrence. Although the design calls for a limit of 55,000 lb NEW in the SRA, the capacity of some railroad cars is 80,000 lb NEW. Some aspects of the 80,000 lb NEW thermal hazards were examined even though the SRA may not be rated to handle an explosive mass of that magnitude.

HIGH PERFORMANCE MAGAZINE DESIGN

DESCRIPTION OF DESIGN

The HP Magazine, consists of a dirt-covered box structure forming a rectangular foor plan with a vehicle portal and a personnel passageway. The facility interior dimensions are 230 feet, 49 feet and 28 1/4 feet for length, width and height respectively. The magazine is covered with 2 feet of soil above the ceiling. The design includes right and left weapon storage bays covered with slideable pit covers and separated by the SRA, which is used for vehicle parking and ordnance loading. Each storage bay consists of two storage pits each 82 feet long by 20 feet wide by 15 1/2 feet deep and separated longitudinally by a transfer aisle. Each storage pit is divided into storage cells by relocatable modular cell walls. The storage cell walls separate the different storage compatibility groups of containerized and palletized munitions and limit the quantity of explosive in any cell of 30,000 lb NEW. Munitions are transferred from the SRA to the pits by means of an overhead crane. Additional drawings and descriptions are included in References 1 and 2.

The region covered by the HP Magazine Type II forms an area 234 feet long by 153 feet wide. Each storage bay has internal space of 82 feet in length by 20 feet in width by 15 1/2 feet in height. Tandem bays are separated by walls and elevated transfer aisles. Vertical height to the ceiling above the overhead bridge crane is 11 1/4 feet. The SRA is 66 feet long by 65 feet wide. General layout and arrangement of the HP Magazine design are illustrated in Figures 1 and 2.

PHYSICAL PRINCIPLES

THERMAL ANALYSIS

Thermal analysis of the ordnance in the storage cells consisted of determining the temperature distributions in the energetic material within the ordnance as a function of time by accounting for the flow of thermal energy, energy addition, production, absorption and/or removal. The equation for heat conduction in a solid with internal heat generation rate may be expressed in differential form as:

EQUATION

$$\rho c_p \frac{\partial T}{\partial t} = \nabla (k \ \nabla T) + q$$

where the symbols represent the following parameters: T for temperature, t for time, ρ for density, c_p for specific heat, k for thermal conductivity, and q for internal volumetric heat generation rate. The Laplacian operator ∇^2 can be written in cylindrical coordinates as $\partial^2/\partial r^2 + \partial/r\partial r + \partial^2/(r^2 \partial\theta^2) + \partial^2/\partial z^2$ where r, θ and z are radial, angular and axial dimensions respectively.

Most munitions can be modeled adequately using angularly-invariant cylindrical approximations. Further discussion of general principles is covered in a variety of textbooks. Means of heat transport include conduction, convection and radiationall of which play a role in the HP Magazine application.

The zero-order Arrhenius equation (neglecting solid mass loss from decomposition) has been found to provide good correlation for the energy generation rate in energetic material as a function of temperature. Critical temperature or time from a specified bulk temperature to cookoff under an isothermal condition have been developed for the Arrhenius exotherms. The energy conservation equation with zero-order Arrhenius kinetics substituting the internal generation term is known as the Frank-Kamenteskii equation:

EQUATION

$$\rho c_p \frac{\partial T}{\partial t} = k \nabla^2 T + \rho Q Z e^{-E/RT}$$

where the generic heat generation rate has been replaced with a reaction heating term in which Q is heat of decomposition, Z is collision number, E is activation energy and R is the universal gas constant. A more extensive discussion of initiation from thermal cookoff can be found in References 3 and 4.

FLUID MECHANICS

Heat propagation through the HP Magazine requires evaluation of confined gas flow using a Computational Fluid Dynamics (CFD) code. A fire in a partially enclosed space requires evaluation of buoyancy forces and ventilation mass flow, especially with the introduction of gaseous reaction products into the room. Reference 5 provides two equations which parameterize this problem and include descriptions of volume flux and time to ventilate the enclosed space:

EQUATION

$$\frac{dV}{dt} = A^* \sqrt{g \frac{\Delta \rho}{\rho} \Delta z} \quad \text{, and}$$

$$t_e = \frac{2A_f}{A^*} \sqrt{\frac{z_c \rho}{g \Delta \rho}}$$

where V represents the volume, g gravitational acceleration, ρ (gas) density, z_c and Δz heights from floor to ceiling and from layer interface to ceiling, respectively, A_f and A^* the floor surface area and ventilation area, respectively, and t_e the ventilation time.

NUMERICAL METHODS

Closed form solutions of heat transfer and fuid transport problems can be obtained for only a small class of problems with severely simplified assumptions. For problems of a more complex nature either in terms of initial and/or boundary conditions, elaborate geometry, or nonlinear material properties, numerical techniques are employed. Such problems are usually formulated as input data to a variety of pre-existing computational codes that can be executed on electronic computers. In numerical computational models, the object of study is broken down into smaller discretized and interconnected control volumes and evaluated either explicitly or implicitly, depending on the code and its applications.

SOURCES FOR PROPERTY DATA

Physical property characteristics were obtained for a variety of materials. Properties such as density, thermal conductivity and heat capacity for most commonly used aerospace metals can be found in Reference 6. Values for less common materials such as chemically-bonded ceramic (CBC) used in the construction of wall facing and pit covers has been provided by NFESC.

In addition to thermal characteristics, evaluation of energetic materials as incorporated in explosives, rocket motors and fuels requires values for additional parameters such as activation energy, heat of decomposition and collision frequency. The values were obtained primarily from References 7 and 8. The heat of reaction determined for cookoff donor is taken as the heat of explosion plus 20 percent of the difference between the heat of explosion and heat of combustion. Empirical values for heat of explosion are based on reaction in the absence of oxygen, while those for heat of combustion are based on an environment of pure oxygen. For combustion of explosives in air at standard pressure, oxygen in the environment would contribute to the heat addition due to the fuel-rich nature of the energetic material composition consumed in the reaction and formulated to mitigate shock sensitivity.

COMPUTATIONAL MODELING TECHNIQUES

ORDNANCE MODELS

Thermal threshold criteria for cookoff of acceptor ordnance were predicted using numerical models. First, geometric constructions were generated for axisymmetric shapes, or three-dimensions for non-axisymmetric designs. These geometric constructs were developed using either PATRAN or SINGEN, which were then translated into a finite-difference thermal-node network. The PATRAN geometric modeling code is described in detail in Reference 9. The corresponding PATSIN translator is described in Reference 10. The files with their respective thermal nodes and connectors were adjusted to include the desired boundary and initial conditions as well as Arrhenius coefficients and their respective cookoff determination subroutines. The thermal-node network models are executed using the System Improved Numerical Differencing Analyzer (SINDA) thermal analyzer code. SINDA utilizes lumped mass properties for each node and performs an energy balance for the nodes by calculating heat conduction for each nodal path in the model at each time step. Heat transfer between nodes i and j can be expressed as $Q = G (Ti - Tj)$, where Q represents the heat transfer, G denotes the effective conductance (due to conduction, convection, radiation or mass transport) and T represents the temperature for nodes i and j. Capabilities and numerical techniques of this code are covered in Reference 11. The models were created and executed on a Silicon Graphics 4D/340 VGX computer. The resulting output provides temperature values for each node as a function of time. Results were translated back to PATRAN for post processing using a variety of graphics options. The temperature data were illustrated through contour plots showing distributions along and/or within the object of study, or linear plots graphing values at specified positions in the model as a function of time or at specified times with respect to material depth.

After the munition thermal network model was created, a uniform initial temperature was imposed. Boundary conditions induce a transient heat transfer condition on the model exterior, and the nodal temperature values are adjusted to balance the energy conservation equation. Exothermic chemical reaction from the Arrhenius kinetics contribute heat addition to the energetic material nodes, thereby increasing their respective temperatures. For each time step, nodal temperatures either reach equilibrium or rapidly increase to some high value indicating rapid exothermic decomposition has occurred which would result in an irreversible event: mechanical rupture, deflagration, detonation, etc. Two subroutines in the code determined the prediction of thermal cookoff reaction. The first subroutine calculated the thermal energy created in a node from the chemical decomposition using the current temperature of the node. The nodal temperature was then correspondingly updated. The second subroutine compared the difference between the current and the previous temperature at that node. If the change in temperature over a given time period exceeded 1000íF/sec the reaction was said to occur. The time, temperature, and node identification (and hence location) of the predicted reaction was recorded and the run terminated.

HP MAGAZINE MODELS

The gas flow in the HP Magazine resulting from an internal combustion source has been evaluated using a code from the National Institute for Standards and Technology (NIST) called the Consolidated model of Fire growth And Smoke Transport (CFAST). The CFAST code procedure and algorithms are explained in Reference 12; additional discussion of the theory is provided in Reference 13.

Due to the complex nature and broad scales involved in combustion propagation in con 'ned spaces, CFAST utilizes a finite-element zone or control volume approach. Conservation laws are established for a two-layer model solving the following equations of changes in pressure P, zone volume V and zone temperature T :

EQUATION

$$\frac{dP}{dt} = \frac{\gamma - 1}{V}\left(\dot{H}_U - \dot{H}_L\right)$$

$$\frac{dV_U}{dt} = \frac{1}{\gamma P}\left[(\gamma - 1)\dot{H}_U - V_U \frac{d\,\Delta P}{dt}\right]$$

$$\frac{dT_{U,L}}{dt} = \frac{1}{c_p\, \rho_{U,L} V_{U,L}}\left[\left(\dot{H}_{U,L} - c_p\, \dot{m}_{U,L} T_{U,L}\right) + V_{U,L}\frac{dP}{dt}\right]$$

where $\dot{H}$ is total enthalpy, γ is the ratio of specific heats, $\dot{m}$ is the mass flow rate, and subscripts $(\,)_U$ and $(\,)_L$ represent upper and lower gas layers.

A CFAST model of the HP Magazine was created by constructing a series of connected volumes corresponding to the design dimensions. A heat source was specified by location, energy and duration, and the gas temperature response of the resulting gas layers was determined as time progressed. Post processing capabilities included display of thermal layer depth relative to the dimensions of the cavity being modeled, as well as temperature at specified locations with respect to time.

The wall temperatures were calculated from a one-dimensional flat plate SINDA model. The model evaluated the wall temperatures as a function of time and depth in response to an imposed temperature environment.

ORDNANCE MODEL SELECTION AND VALIDATION

Evaluation of the HP Magazine thermal hazard required determining the worst case donor and acceptor munitions. This facilitated the selection of ordnance examples to model.

The worst case donors and acceptors for thermal cookoff were identified and are provided in Table 1 below for the different HP MagazineStorage Comparability Group (SCG) Categories. In particular, groups 2 (liquid fuels and explosives), 4 (HE bombs), and 8 (rocket-powered missiles) were assessed as potentially causing the most serious damage in the HP Magazine. Italics denote items evaluated.

TABLE 1. Worst Case Thermal Donor and Acceptor Munitions in HP Magazine Storage Compatibility Groups

SCG Category	Worst-Case Donor	Worst-Case Acceptor
1 initiators, fuses...	#8 Blasting Cap	#8 Blasting Cap
2 flam. liq. & expl.	Tomahawk Cruise Missile	*Tomahawk Cruise Missile*
3 incendiary mun.	106 mm Cartridge	106 mm Cartridge
4 bombs	Mk 82 or Mk 83 Bombs	*Mk 82* or Mk 83 *Bombs (H-6 fill)*
5 demolition expl.	Flex. Linear Shaped Charge	M118 PETN Demolition Block
6 cluster munitions	M433 Series Bomblet	M433 Series Bomblet
7 directed energy	Mk 122 Warhead	TOW / ITOW / TOW II
8 thin-skin missiles & torpedoes	Mk 73 Standard Missile w/ Mk 104 Rocket Motor	*Mk 73 Standard Missile* w/ Mk 104 Rocket Motor

TABLE 1. Worst Case Thermal Donor and Acceptor Munitions in HP Magazine Storage Compatibility Groups

COOKOFF THRESHOLD CRITERIA

THERMAL REACTION

Isothermal cookoff threshold models were developed for the Tomahawk cruise missile, MK 82 bomb, and the Standard missile for the HP Magazine SCG Categories 2, 4 and 8, respectively. Each munition was modeled using PATRAN or SINGEN to develop a two-dimensional or three-dimensional nite element grid which was then translated to a SINDA model. Boundary conditions of different constant ambient temperatures were applied to the models to produce cookoff thresholds. By maintaining the ambient temperature constant for a specific duration and then dropping it to a lower temperature (100íF) before a reaction, a point-of-no-return (PNR) can be found. That point in time represents the longest period that a munition can be maintained within a constant ambient temperature field and avoid an energetic reaction. The constant temperature condition was chosen to facilitate comparisons between munitions. Each model included convection and radiation from the ambient source to the munition. Based on fuel-fire tests, convection rates of 4.0 Btu/hr-ft2-íF and 3.0 Btu/hr-ft2-íF were used for bombs and missiles respectively, and a hot gas emissivity of 0.9 was used for radiation emissivity. Within the munition, self heating of the energetic material was modeled through a subroutine.

The thermal network models for munitions described in the following paragraphs were generated and executed for isothermal conditions in order to evaluate thermal cookoff sensitivity. A given constant temperature was imposed for a specified duration and then reduced to 100íF. Different boundary condition temperatures between 400íF and 2000íF were applied to determine isothermal reaction times. The duration of the higher imposed boundary temperature was successively reduced until a cookoff prediction no longer occurred for each chosen constant temperature. The threshold plots for the evaluated munitions presented in this section are shown in Figures 3 through 7. Each plot includes three curves. The curve on the left is the PNR, an elevated temperature exposure duration beyond which cookoff is inevitable. The middle curve represents the isothermal reaction time to cookoff. The curve on the right is the predicted maximum time prior to cookoff after isothermal exposure to the PNR and subsequent quench to a 100íF ambient condition. Isothermal exposure of munitions must be limited in duration depending on the temperature level to the left side of the PNR line in order to avoid cookoff. This defines the limit of munition sensitivity to thermal hazards.

MK 82 GP BOMB

The Mark 82 general purpose (GP) 500 lb bomb has a 10-inch diameter and is about 91 inches in length. The case is composed of a 0.4-inch thick steel pipe which has been deformed to a specified shape. Cables are inserted and connected to the fusewell. The inner wall is coated with a liner and the cavity is then filled with 180 lb of H-6 explosive. A thermal protection material (TPM) MIL-C-81904 covers the outside surface of the Mod 2 version. An axisymmetric model representing a one-inch wide segment of the bomb near the midpoint of the axial length (at the bombs widest extent and the minimum thickness of the case) was created using SINGEN and translated to the thermal network analyzer SINDA. The model was first executed for a fuel fire boundary condition and compared to test data in Reference 14 to verify the accuracy of the code. Boundary conditions were then incorporated using an isothermal heat source with convection and radiation for a specified duration to determine the time to reaction. Plots of time to reaction versus ambient temperature are illustrated in Figure 3.

STANDARD MISSILE

Three components were modeled for the Standard RIM-67A surface-to-air missile to determine which had the shortest duration to thermal response: the warhead, the rocket motor, or the booster. The warhead and rocket motor are stored together in a rectangular aluminum case with about 4 inches of clearance from the inside walls. The booster is stored in a similar separate case also with about 4 inches of clearance. The Standard warhead is composed of a steel case filled with PBXN-106. The case is insulated to protect its electronic components during high speed flight and therefore would be better protected during a magazine fire than other missiles. The motor and booster have steel cases and are loaded with NWC-111. The complete missile weighs 2990 lb; its basic dimensions are a length of 324 inches and a 13.5-inch diameter. Ambient temperature versus time threshold plots are shown in Figures 4 through 6 for the three components. Figure 4 illustrates (from left-to-right) the calculated PNR, isothermal reaction and maximum delay curves for the Standard rocket motor. Figure 5 shows these same three curves calculated for the Standard warhead. The furthest right curve showing maximum reaction time appears more erratic for the warhead than for the motor or booster. Due to a thermal lag from its insulation, the accuracy of the longest reaction time for the warhead is much more sensitive to the precision of the PNR. Thus, where ±10-second accuracy for the PNR time calculations yielded comparatively smooth plots for the propellants, ±1-second accuracy would have been needed to get similar quality of results for the warhead. To avoid extensive computations, the results from the ±10-second accuracy runs were used for these graphs. Figure 6 shows these three curves for the Standard booster.

TOMAHAWK CRUISE MISSILE

A three-dimensional model of the BGM-109 Tomahawk jacketed warhead was created to include radiation and convection heat transfer to the missile container. From the container, heat was radiated and convected to the missile surface. The Tomahawk differs from other missiles in that the design incorporates a liquid fuel tank that wraps around the warhead. Diameter of the warhead and fuel jacket are 15 and 21 inches respectively. The overall missile is 252 inches in length. Heat from the surface of the missile was conducted and convected into and through the JP-10 fuel and then to the warhead. Self heating was modeled within the warhead energetic material PBXN-107. The fuel was assumed to auto-ignite at 474íF. The Tomahawk was determined to cookoff when either the fuel auto-ignited or the energetic material reacted. Plots of time to reaction versus ambient temperature are shown in Figure 7. For the 600íF and 800íF isothermal conditions, the explosive reacted before the fuel; at 1000íF and above, the fuel auto-ignited first. The Tomahawk model was validated by matching test data was reported in Reference 15.

ORDNANCE SENSITIVITY TO COOKOFF

The three HP Magazine SCG categories studied are susceptible to cookoff given the appropriate heating conditions. The cookoff threshold criteria graphs illustrate temperature history exposure zones in which the munitions react or remain safe. Each graph was derived by imposing a constant temperature boundary condition on the munition for a predetermined duration. In an actual fire within the HP Magazine, the internal gas temperature would not behave so orderly. By utilizing constant temperature inputs, the different munitions can be compared with each other for cookoff sensitivity relative to thermal boundary conditions. Figure 8 compares the isothermal cookoff threshold plots of predicted temperature versus time for the Tomahawk cruise missile warhead, MK 82 bomb, and the three segments of the Standard missile. At temperatures above 1000íF, the MK 82 bomb and the Standard rocket motor and booster motor have about the same sensitivity. The Tomahawk is less sensitive than the three aforementioned munitions due to the large thermal mass of fuel, and the Standard warhead is least sensitive due to its insulation. Figure 9 compares the PNR plots of temperature versus time for these same munitions. At constant temperatures below 1000íF, the MK 82 bomb is the most sensitive. At about 1100íF and higher, the Standard rocket motor and the booster motor are more sensitive than the bombs. For the higher temperatures, the thermal protection layer on the MK 82 bomb insulates the energetic material thereby forestalling the condition of a runaway exothermic reaction. The Standard motor incorporates a thin case which allows heat to rapidly enter the propellant.

Sensitivity of ordnance to thermal cookoff can be examined through a time-energy-generation-rate history for a munition exposed to a high constant-temperature environment for a specified period near the PNR. Values of heat generation rate over selected time intervals were tabulated from the execution of the one-inch-long cross-section thermal model of the Standard booster motor. A constant ambient temperature condition of 2000íF was incorporated for durations of 155 and 160 seconds. The ambient temperature was then decreased to 100íF and held constant. The heat generation rate for the 155 seconds duration leveled off at a maximum of 0.006 Btu/sec and then gradually diminished to a lower level indicating a non-cookoff condition. A duration of 160 seconds at 2000íF led to cookoff after the rate for the 155-second duration case had passed its maximum internal heat generation rate. A similar analysis was conducted using 1000íF as the constant ambient temperature for 1160 and 1165 seconds duration. For the 1160-second case, heat generation rate leveled off at 0.012 Btu/sec before decreasing. (This value represents a consumption of energetic material at 44 gm/hr - a rate which would be maintained for only a few minutes, resulting in minute quantities of material expended. The 44 gm/hr rate demonstrates that the zero order Arrhenius assumption is valid.) The higher tolerated energy rate for the lower ambient temperature indicates that a lower rate of source heating yields a longer period before cookoff by dissipating energy faster to both ambient air and motor interior. The heat generation rate versus time for these cases are illustrated in Figure 10. These energy plots are typical for munitions in general. The bifurcation point in elevated temperature duration was determined to within ±5 seconds for each munition discussed above and plotted as the PNR.

HP MAGAZINE AIR MODEL RESULTS

For a case of a 30-minute combustion MCE in the SRA burning 55,000 lb of energetic material (EM), the gas in the HP Magazine had a (dimensionless) Rayleigh number of about ten-trillion,

EQUATION

$$Ra = g\,\beta\,c_p\,\rho^2\,L^5\,q\,/\,\mu\,k^2$$

where g, β, L and μ are gravitational constant, thermal expansion, length and viscosity, respectively

indicating that buoyancy forces greatly exceed viscous forces, and hence enabling inviscid algorithms to evaluate mass and heat transport. A code developed by NIST named CFAST was found to provide the needed capability.

CFAST is a finite element code that divides the gas volume of each zone or room into upper and lower buoyancy driven layers. CFAST solves a set of equations that predict state variables (pressure, volume, and temperature) based on the enthalpy and mass flux over small increments of time. Combustion is modeled by enthalpy and mass release at a specified rate. Two mechanisms exist for enthalpy and mass transport between the layers within and between rooms: the 're plume within the room, and the flow through openings such as doors or vents. The degree of mixing is based on an empirically derived relation. CFAST allows for heat transfer to occur between the layers, across horizontal boundaries and to room surfaces. A three-dimensional zone model of the HP Magazine Type II was constructed using CFAST and was executed for several combustion conditions and venting congurations as detailed below.

Heat generation was modeled by an estimate of the output from the burning of H-6. The heat of reaction used for H-6 was 6.48Ñ106 J/kg (=1.55 kcal/gm = 2.79Ñ103 Btu/lb); this value was used for all cases. The heat of reaction was determined as the heat of explosion plus 20 percent of the difference between the heat of explosion and heat of combustion. (Empirical values for heat of explosion are based on reaction in the absence of oxygen, while those for heat of combustion are based on an environment of pure oxygen.) For combustion of explosives in air at standard pressure, oxygen in the environment would contribute to the heat addition due to the fuel-rich energetic material.

Due to the absence of adequate empirical data on heat transfer under the conditions being modeled, the following assumptions were used. The donor energetic material was entirely consumed via combustion thus maximizing the heat transfer to the environment (worst case thermally). The duration of the donor fire was established at 30 minutes. Air temperature in the acceptor munition storage cell was identical to the hot gas layer from instantaneous mixing (worst case). Heat was radiated to the munitions from the hot gas layer with an emissivity of 0.9, taken from Reference 16. The emissivity of the munition surface was conservatively estimated at 0.9. The model configuration assumed that the pit covers were not protecting the acceptor munitions, thus allowing the hot gas layer to mix with the storage cell air and radiate heat onto the munitions.

Table 2 shows the matrix of EM quantity, MCE location, combustion duration, and venting configurations examined with CFAST. The EM quantities and corresponding MCE Locations were combined with the listed Fire Durations and Venting / Ceiling Configurations. The vents, where present, were either located on the walls flush with the ceiling and distributed uniformly throughout the magazine, and/or in the raised ceiling area of the SRA. The "Caboose" refers to a proposed mitigation design where the ceiling above the SRA is elevated one meter (thus giving the box-like magazine interior a caboose-like shape). In this elevated area, the vents were placed evenly around all four walls flush with the top of the raised ceiling. The model accounted for venting through the tunnel entrance.

TABLE 2. CFAST Input Matrix.

EM Quantity	MCE Location	Duration	Vents / Ceiling Type
55,000 lb EM	SRA	30 min	None / Flat Ceiling
		20 min	8 (1 x 0.5m) / Flat Ceiling
			10 (1 x 0.5m) / 1m Caboose
			4 (1 x 0.5m) / Vents in Caboose only
			8 (1 x 0.5m) / Vents in Caboose only
80,000 lb EM	SRA	30 min	None / Flat Ceiling
		40 min	8 (1 x 0.5m) / Flat Ceiling
			10 (1 x 0.5m) / 1m Caboose
10,000 lb EM	Cell	30 min	None / Flat Ceiling
			8 (1 x 0.5m) / Flat Ceiling
			10 (1 x 0.5m) / 1m Caboose
20,000 lb EM	Cell	30 min	None / Flat Ceiling
		20 min	8 (1 x 0.5m) / Flat Ceiling
		10 min	10 (1 x 0.5m) / 1m Caboose
30,000 lb EM	Cell	30 min	None / Flat Ceiling
			8 (1 x 0.5m) / Flat Ceiling
			10 (1 x 0.5m) / 1m Caboose
			4 (1 x 0.5m) / Vents in Caboose only
			8 (1 x 0.5m) / Vents in Caboose only

TABLE 2. CFAST Input Matrix

Figures 11 through 20 illustrate temperature time-histories in the upper hot gas layer in the SRA and a storage bay. The upper layer is composed of hot gas and the lower layer is the cooler air. CFAST calculated the vertical height of the hot upper gas layer. In all of the cases run, the hot gas replaced the ambient air and FIlled the horizontally contiguous spaces within 90 seconds of the combustion MCE initiation. Although the air in the storage pits is buoyantly isolated from the magazine entrance and hence would not escape, mixing from convection and diffusion would be expected to equilibrate the cell temperature to values approximating the upper layer before a fire in the SRA would be exhausted. The graphs described in the following paragraphs depict average upper layer temperatures in the SRA and the right storage bay. Ventilation configurations include a) no mitigation, b) distributed vents and a flat ceiling, c) distributed vents in the bay and caboose, and d) caboose vents.
The case of four 1 x 0.5 meter vents located in the caboose were excluded from the plots since the difference from eight such vents was negligible. Of primary interest are the temperatures of the acceptor regions since conditions in those locations represent the

secondary MCE hazard. The temperatures in the respective donor MCE locations are included in these plots for comparative purposes.

The results for a 55,000 lb EM 30-minute combustion MCE in the SRA plotted in Figure 11 compares the different venting schemes. For these scenarios, the temperature in the storage bay is greatest for some venting within the bay. Venting draws more of the hot gas into the bay area, but it also allows the bay area to cool faster after the MCE ends. The 8-vents-caboose con 'guration provides the least severe bay temperatures during the fire but does not cool the bay down as fast as alternate schemes after the fire. The different venting configurations changed the temperatures about 100íF in the bay area and 200íF in the SRA. A 20-minute combustion MCE with 55,000 lb EM in the SRA was also examined to determine the effects of a faster burn rate. Figure 12 shows a comparison of a 20-minute fire to a 30-minute fire for a no-venting case. While the peak temperature in the SRA increases by about 400íF for the shorter duration MCE, the maximum temperature in the storage bay is nearly the same for the two conditions.

Figure 13 shows the temperature values for the different venting conditions for an 80,000 lb EM 30-minute fire. A comparison between 30- and 40-minute combustion MCE durations is shown in Figure 14. The temperature in the SRA is lower in the 40-minute fire because the reaction-product gases released have more time to vent out the magazine entrance. The temperatures in the storage bay are comparable for both conditions. Figure 15 shows a comparison of a 30-minute SRA combustion MCE of 80,000 lb EM and 55,000 lb EM consumed. The former increases the temperature in the storage bay by about 100íF over that of the latter.

Three different MCE fires within the storage cells were modeled. The first model used 10,000 lb EM for a 30-minute fire. Figure 16 shows a comparison of venting schemes. In the cell fire plots, the higher temperatures were found, as expected, in the storage bay region. The bay temperature for the no-venting case peaks at about 900íF then drops back down to 850íF before starting a slow rise. This peak is caused by the hot combustion gas accumulation before the gas pressure forces venting through the tunnel entrance. The bay temperatures of the non-venting case are generally lower than for the venting cases due to the inhibition by the vents of the tunnel entrance in drawing most of the hot gas away from the bay towards the SRA. Figure 17 shows the temperatures for a 30-minute 20,000 lb EM combustion MCE in the cell, intended to model a storage bay loaded with missiles (SCG Category 8). Due to the faster rate at which propellant burns compared to explosives, the 20,000 lb EM condition was also executed for fires of 20- and 10-minute durations to a simulate missile donor MCE. Figure 18 shows a comparison between 10-, 20-, and 30-minute cell fires. As expected, reducing the combustion duration increases the gas temperatures, but all three cool down more quickly than aforementioned scenarios in the SRA. Figure 19 compares venting scenarios for a 30,000 lb EM 30-minute cell combustion MCE. Figure 20 shows a comparison between NEW quantities of 10,000; 20,000; and 30,000 lb EM in 30-minute cell fires with no venting.

CFAST allows for the room surfaces to absorb some of the heat produced by the fire, but flexibility was limited. A lumped-mass model of the entire magazine air volume was created in SINDA (see below) to better determine the absorption of heat by the floor, walls, and ceiling. SINDA is more accurate than CFAST in calculating heat absorption from the gas by the magazine surfaces, but the accuracy in determining the gas heating and venting is constrained. An assessment of the combined mitigation effects and the two modeling techniques used to calculate gas temperatures is discussed below.

HP MAGAZINE SURFACE TEMPERATURE MODEL RESULTS

HP Magazine surfaces were evaluated in order to establish characterization of the structure as a heat transfer medium and passive mitigation device. The concrete and the chemically-bonded ceramic (CBC) were examined under a combustion MCE condition to evaluate material temperature with increasing depth. In addition, the mitigation technique of increasing surface area to facilitate heat absorption by the structure was investigated.

The HP Magazine structure is primarily constructed from concrete but the pit covers and relocatable walls are composed of CBC. The average surface temperatures of the surfaces within the HP Magazine were computed using the SINDA model described above which assumed a bulk air temperature. Figure 21 shows the temperature of the concrete surfaces (walls and ceiling) at depths of 0.25, 0.5, 0.75, and 1.0 inches. Depending on the type of concrete, the penetration of heat induced spalling may lead to structural damage and should be further investigated. Figure 22 shows the temperatures of the CBC surfaces (pit covers) at depths of 0.25, 0.5, 0.75, and 1.0 inches. Although the surface temperatures of the CBC pit covers are hotter than the surface temperatures of the concrete, the heat transfer is less rapid in the CBC due to its lower thermal conductivity. Temperature gradients for the modeled conditions from the surface to the first inch of depth are about 800íF/inch and 1200íF/inch for concrete and CBC, respectively. One may conclude that the CBC pit covers present an adequate insulating barrier from MCE donor combustion gases for munitions contained in a storage bay.

To investigate the effect of increasing magazine surface area to increase heat absorption and thereby reducing the gas temperature from a combustion MCE, a SINDA model was developed to estimate the temperatures of the hot gas and magazine surfaces. Such an increase in effective surface area can be achieved using multiple indentations in the surface ceiling design. This type of pattern can be described as a “waffle” texture in appearance. For this analysis, the area increase was taken as a factor of two. The model incorporated the thermal energy from a 30-minute combustion MCE consuming 55,000 lb EM in the SRA and did not include any venting of the hot gas produced by the fire. These temperatures represented a bulk average for the gas in the entire volume of the HP Magazine, and thus are cooler than the SRA temperatures and hotter than the bay temperatures predicted by CFAST. Bulk gas temperatures within the HP Magazine are plotted in Figure 23. The curves compare the gas temperatures for heat absorption by the flat versus double-area ceiling surfaces within the HP Magazine. The temperature difference produced by doubling the surface area of the ceiling and walls is also shown in this graph and reaches a maximum temperature reduction from flat to waffle ceiling of more than 300íF.

To compare the data from the CFAST code and the SINDA code, Figure 24 was generated. The graph shows temperatures for a 55,000 lb EM 30-minute combustion MCE in the SRA as calculated by CFAST and SINDA. The CFAST code accounts for venting through the tunnel entrance while the SINDA code models heat absorption by the surfaces more accurately. SINDA incorporates lumped masses to represent the gas and magazine surfaces, and compares the effect of increased surface area “flat ceiling” representing the baseline condition, while the indented (or “waffle”) configuration would increase this same wetted area of the same volume. The CFAST model was used to insure the validity of the lumped mass approximation by comparing the temperatures in the SRA and bay with the weighted average. The CFAST average temperature is lower than that of the SINDA lumped mass due to the accounting for venting through the tunnel entrance in the former. By combining the effects of indented surfaces and venting, the bay temperatures should be lower than those shown.

ORDNANCE RESPONSE TO FIRE SCENARIOS

Gas temperatures in the bay from the CFAST model for a 30-minute combustion MCE in the SRA were incorporated into the ordnance models to evaluate their cookoff sensitivity. All conditions evaluated herein presumed an open storage cell without an overhead pit cover. A variety of boundary conditions can be imposed from the hot gas temperature to the storage cell. The worst case assumption presupposes that the hot gases completely permeate the storage cell immediately and surround the ordnance stored within. In this event, thermal energy is transported to the munitions by radiation and convection from the hot gas within the cell. The least severe condition assumes that no mixing takes place between the upper hot gas layer and the initial air in the storage cell. Under these circumstances, the heat from the hot gas only penetrates a few feet of the ambient cell air from the top of the cell and radiation provides the primary heat transfer path from the upper hot gas layer to the munition. Due to computational limits total mixing has been assumed for the ambient temperature boundary condition on all munition response models to the sundry combustion profiles generated from CFAST. A free convection coefficient of 1.0 Btu/hr-ft2-íF and a hot gas emissivity of 0.9 were used throughout these models. Both the Standard Booster and the MK 82 bomb were examined because they had the most sensitive cookoff thresholds. Pit covers, providing a barrier from the hot gas to the munitions, incorporate a small air gap to facilitate locomotion, but these gaps are insufficient in size to enable gas transport into a cell absent a (nonexistent) pressure gradient.

A graph of thermal energy generation of the Standard booster under various MCE scenarios is illustrated in Figure 25. The curves show that for exposure to the unmitigated bay temperatures the booster would cookoff. If the bay temperature differences were reduced by about 200íF through venting and increasing the ceiling surface area, the booster was predicted to cookoff if exposed to a view factor of unity, but survive if this value was reduced to 0.7. The view factor from the hot gas to the munition is defined as the fraction of radiant energy from the gas and imposed on the munition. Since the munitions stored in the HP Magazine will not have all their outer surfaces exposed, most will be stacked on pallets or in containers, and have part of their surfaces pointed away from the hot gas source leading to a view factor less than unity. Calculations to determine the view factors for different stacking arrangements were not done for this study, but a bomb stacked on the upper corner of a pallet (the most exposed) would be shielded by its neighbors. By setting the view factor in the models to 0.7 (a conservative value) to account for stacking, the booster will not cookoff if the bay temperatures are mitigated.

A similar graph of thermal energy generation for the MK 82 bomb is illustrated in Figure 26. For the MCE condition of 55,000 lb EM in the SRA consumed by fire and no mitigation, the MK 82 bomb reacts as a thermal cookoff, regardless of view factor assumed. In the case of caboose venting and the waffle ceiling and a view factor of 0.7, the bomb survives.

MITIGATION STRATEGIES

Dissipation of the heat before the stored munitions respond in cookoff remains the primary concern for a fire accident within the HP Magazine. A number of techniques were examined; only passive mitigation strategies were investigated due to the possibility of an active system failing during or after a MCE. These mitigation techniques included ventilation in the storage bays and SRA, a raised ceiling design with venting in the SRA (caboose design), indented structural surfaces, and thermal blankets covering the ordnance in storage cells with open pit covers. All of the analyses were performed with the assumption that more than one storage cell would be exposed to the hot donor gases.

The different venting schemes investigated included: 1) vents throughout the HP Magazine, 2) vents throughout with a raised or “caboose” ceiling above the SRA, and 3) vents only in the raised ceiling. The CFAST analysis demonstrated that vents within the raised ceiling provided lower temperatures in the storage bay during a combustion event in the SRA but required a longer period to cool down the magazine interior after the fire. The storage bays get hotter with vents distributed throughout the magazine than with vents only over the SRA because more hot gas is drawn through the bay via their vents. Such vents exclusively above the SRA reduce the peak bay temperatures by as much as 100íF for SRA fires and up to 50íF for storage cell fires.

The purpose of indented ceiling and walls was to increase the wetted surface area of the concrete which allowed it to absorb more heat from the hot gas. The analysis shows that a ceiling with double the baseline surface area reduces the hot gas temperatures by up to 300íF. The analysis was performed using a bulk average gas temperature for the entire magazine. The ceiling is more efficient at absorbing heat for higher temperature environments, meaning that the reduction in temperature rise in the bays would be less than the SRA for most such fire scenarios. A conservative estimate was made that both venting and a “waffle” (or indented) ceiling surface would reduce the peak gas temperatures by about 200íF in the storage bays.

The use of a thermal blanket placed over the ordnance pallets was evaluated for the Standard Missile booster and the Mark 82 bomb. Figure 25 shows that the Standard booster would not survive the heat from a 55,000 lb EM combustion event in the SRA with a 1.0 view factor.

Figure 25 shows similar results for the Mark 82 bomb. Figure 27 shows the effect of using thermal blankets over the Standard Missile booster to mitigate the heating from various hazard scenarios. The graph shows that with a thin (0.05 inch) Kevlar blanket the Standard Missile booster would survive the heat from a 55,000 lb EM SRA fire and a 10,000 lb EM cell fire. With a thick (0.5 inch) blanket the booster would also survive up to a 20,000 lb EM cell fire. The booster would not, however, survive a 30,000 lb EM cell fire even with such a blanket. Figure 28 shows that a thick (0.34 inch) Kevlar 3-ply cover would not adequately protect a Mark 82 bomb exposed to a 55,000 lb EM combustion event in the SRA without magazine gas temperature mitigation, although a substantial (0.85 inch) Kevlar cover or a thick (0.34 inch) Qfelt insulating material would adequately protect a Mark 82 bomb under such conditions. These examples were merely representative and did not constitute a recommendation for a specific material.

CONCLUSIONS

The cookoff threshold models quantified the sensitivity of several different munitions to reach a condition where self-heating will induce a sudden and irreversible reaction. By comparing the threshold plots for three different SCG categories, the Mark 82 bomb proves to be the most thermally sensitive to external heating. The models show that the bombs would not withstand temperatures in the neighborhood of 800íF for more than one-half hour - the expected fire duration. Accounting for initial heat generation and dissipation (cool down) time, the threshold models demonstrate the requirement for preventing the munitions exposure to high temperatures from exceeding critical PNR durations.

This study was conducted with the worst case assumption that more than one storage cell would be exposed along with the SRA after a combustion MCE within either location. If the pit covers remain in place after an energetic event, then hot combustion gases would create a cookoff hazard only in the exposed cell. Also the study assumed that all of the energetic material within the MCE location was consumed by fire at a uniform rate for 30 minutes.

The HP Magazine interior models calculated the temperature environment history within the different sections of the magazine. Heat was generated for various amounts of energetic material located either within the SRA or within a storage cell. The rate of mixing between the upper hot gas layer from the fire and the ambient air within the storage cells was indeterminate, so a worst case condition of total mixing combined with hot gas radiation was assumed and used to calculate the temperatures within the cells. Comparisons were made between different EM quantities, MCE locations, and fire durations. In addition, a variety venting arrangements were compared, leading to the discovery that venting was most effective if restricted to the SRA. The reduction in temperature by venting during the combustion process was determined to be not as significant as hoped for the limited ventilation areas evaluated.

The gas temperature histories generated by the magazine models were applied to the ordnance models used in determining the cookoff thresholds. The results showed that the most sensitive munitions (HE bombs - SCG Category 4) would react (cookoff) when un-mitigated gas temperatures were applied. The munition responses to the temperature histories from different combustion scenarios were compared and it was found that the bombs could survive the 55,000 lb total EM combustion MCE in the SRA only when mitigation was used. The analysis of the cell fires showed that bombs in an uncovered cell would only survive the thermal hazard from a combustion event of up to 10,000 lb EM from another storage cell in the same bay.

The most effective mitigation technique found to reduce gas temperatures is an indented ceiling and structural wall design (to increase surface area) throughout the magazine to improve heat absorption. This technique reduces the gas temperatures within the storage cells from a combustion MCE to acceptable levels. The bomb models did not indicate cookoff response when the mitigated temperature boundary conditions were applied, but the internal heat production rates suggest that only a small margin exists to avoid a reaction, thereby alluding to the importance of thermal protection, either from pit covers or thermal blankets.

REFERENCES

1. Naval Civil Engineering Laboratory. *High Performance Magazine, FY93 Statements of Work for WBS 1.0 Technical Operational Requirements and WBS 5.0: Material Handling System*, W. A. Keenan. Port Hueneme, CA. NCEL TM 51-93-04. 5 March 1993.

2. Naval Civil Engineering Laboratory. *Development of High Performance Magazine for Storage of Ordnance*, W. A. Keenan, Port Hueneme, CA. June 1993.

3. C. L. Mader. *Numerical Modeling of Detonations*, University of California Press, 1979.

4. J. Zinn and C. L. Mader. “Thermal Initiation of Explosives”, *J. of Applied Phys.*, v. 31, no. 2, February 1960.

5. P. F. Linden, G. F. Lane-Serff and D. A. Smeed. “Emptying filling boxes: the fluid mechanics of natural ventilation”, *J. Fluid Mech.*, v. 212, pp. 309-335, March 1990.

6. Department of Defense. *Military Handbook: Metallic Materials and Elements for Aerospace Vehicle Structures*, 2 vol., MIL-HDBK-5E. 1 June 1987.

7. Naval Air Warfare Center. *High Performance Magazine Thermal Event*, J. M. Pakulak, Jr. China Lake, CA. NAWC TP 8091. In Progress.

8. Lawrence Livermore National Laboratory. *LLNL Explosives Handbook* , B. M. Dobratz and P. C. Crawford. UCRL-52997 Change 2. 31 January 1985.

9. PDA Engineering. *PATRAN User's Guide*, Release 2.4, September 1989. Costa Mesa, CA.

10. PDA Engineering. *PAT/SINDA Interface Guide*, Release 3.0, March 1990. Costa Mesa, CA

11. Network Analysis Associates. *SINDA 1987/ANSI Manual*, 21 October 1987. Fountain Valley, CA.

12. National Institute of Standards and Technology. A Programmer's *Reference Manual for CFAST, the Unified Model of Fire Growth and Smoke Transport* , W. W. Jones and G. P. Forney, NIST 1283, 1990.

13. W. W. Jones. "Modeling Smoke Movement through Compartmented Structures", *J. of Fire Sciences*, v. 11, pp. 172-183, March/April 1993.

14. Naval Weapons Center. *Summary Report of Fast Cookoff Times, Reactions, and Hazards of Bombs, Rockets, Aircraft Guns, Air-Launched Missiles, Mines, and Torpedoes* , C. A. Dettling, CDR J. A. Rhodes, USN and B. J. Dettling. China Lake, CA. NWC TP 6914. September 1989.

15. Naval Weapons Center. "Thermal Analysis of Tomahawk 'Y' Warhead Slow Cookoff", R. M. Harris. China Lake, CA. Memorandum 8800/3593-034. 12 July 1991.

16. American Society of Mechanical Engineers. G. D. Raithby and E. H. Chui. "A Finite-Volume Method for Predicting Radiant Heat Transfer in Enclosures with Participating Media", *Heat Transfer Phenomena in Radiation, Combustion and Fires*, HTD-Vol. 106, 1989 National Heat Transfer Conference.

Figure 1. High Performance Magazine Floor Plan

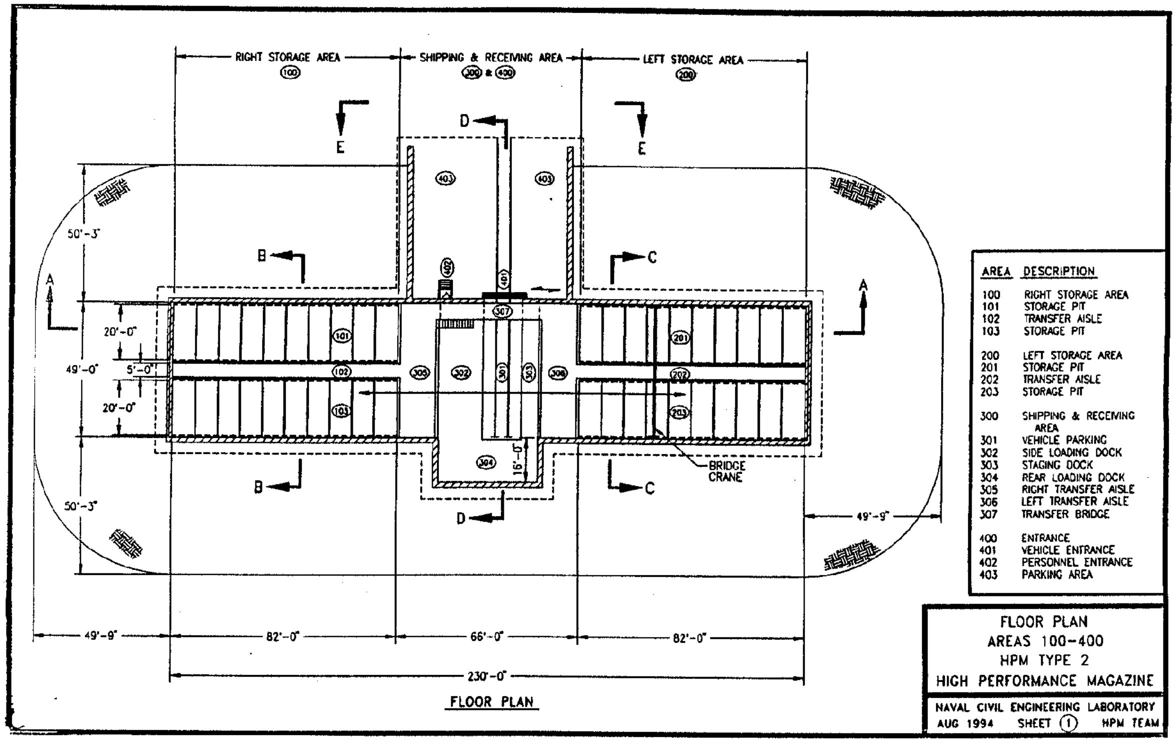

Figure 1. High Performance Magazine Floor Plan

Figure 2. High Performance Magazine Elevation View

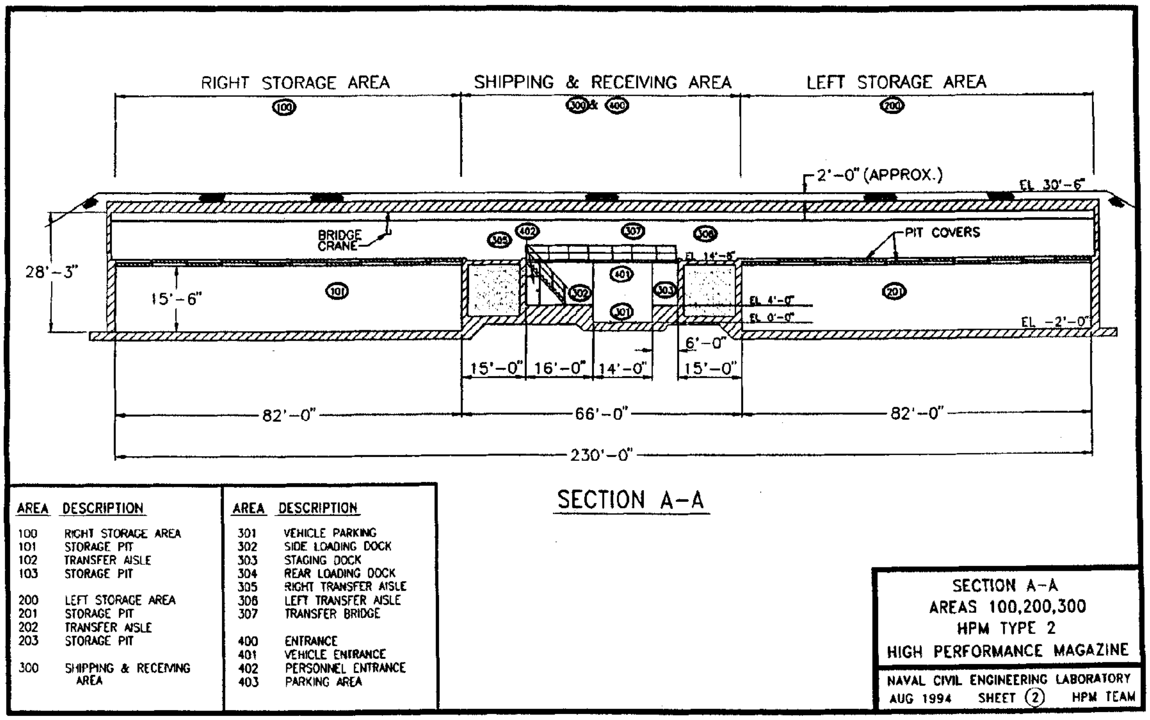

Figure 2. High Performance Magazine Elevation View

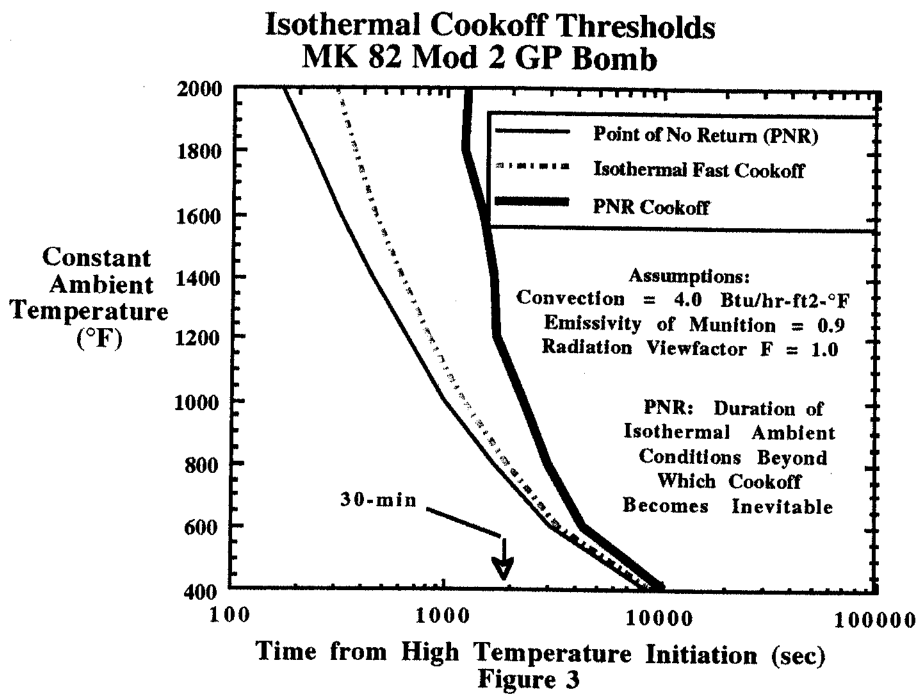

Figure 3 Isothermal Cookoff Thresholds MK 82 Mod 2 GP Bomb

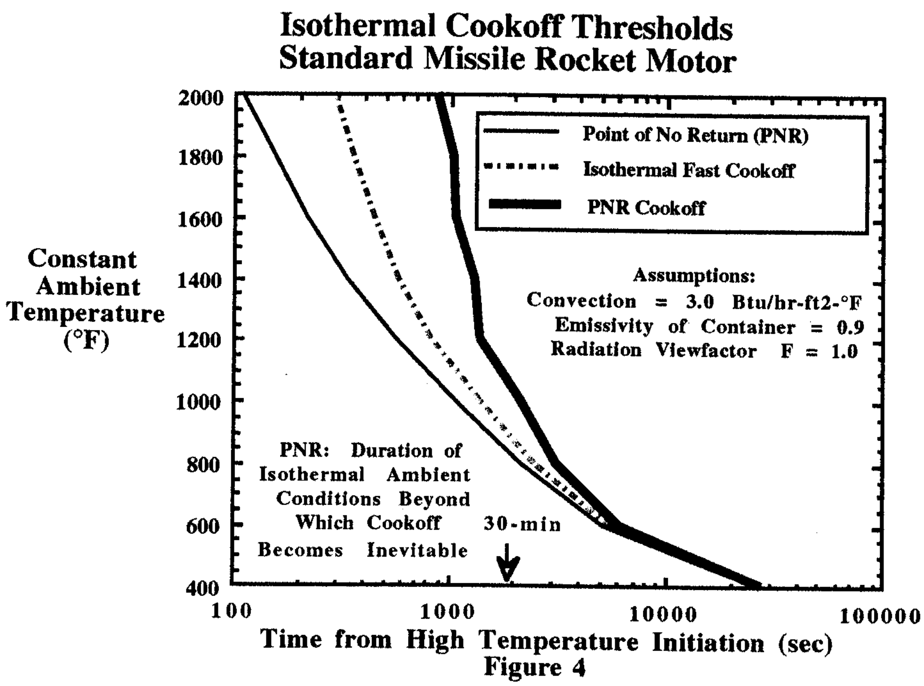

Figure 4 Isothermal Cookoff Thresholds Standard Missile Rocket Motor

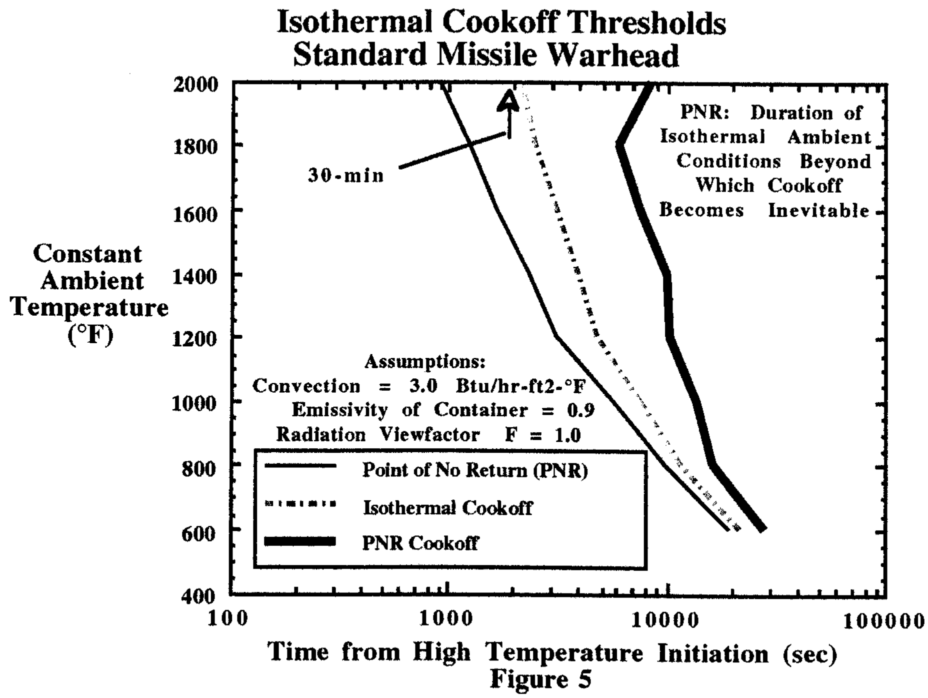

Figure 5 Isothermal Cookoff Thresholds Standard Missile Warhead

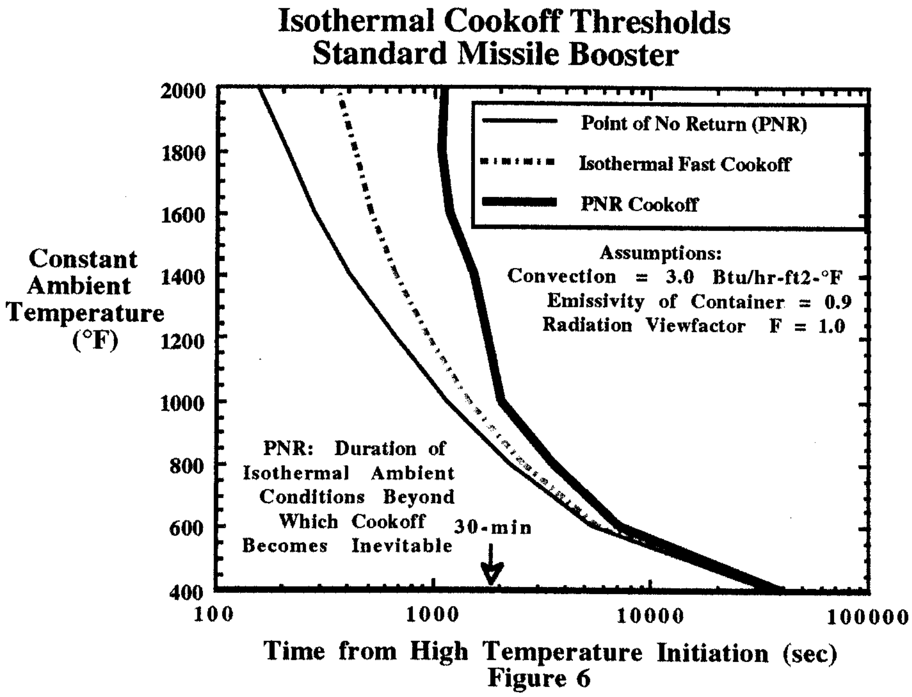

Figure 6 Isothermal Cookoff Thresholds Standard Missile Booster

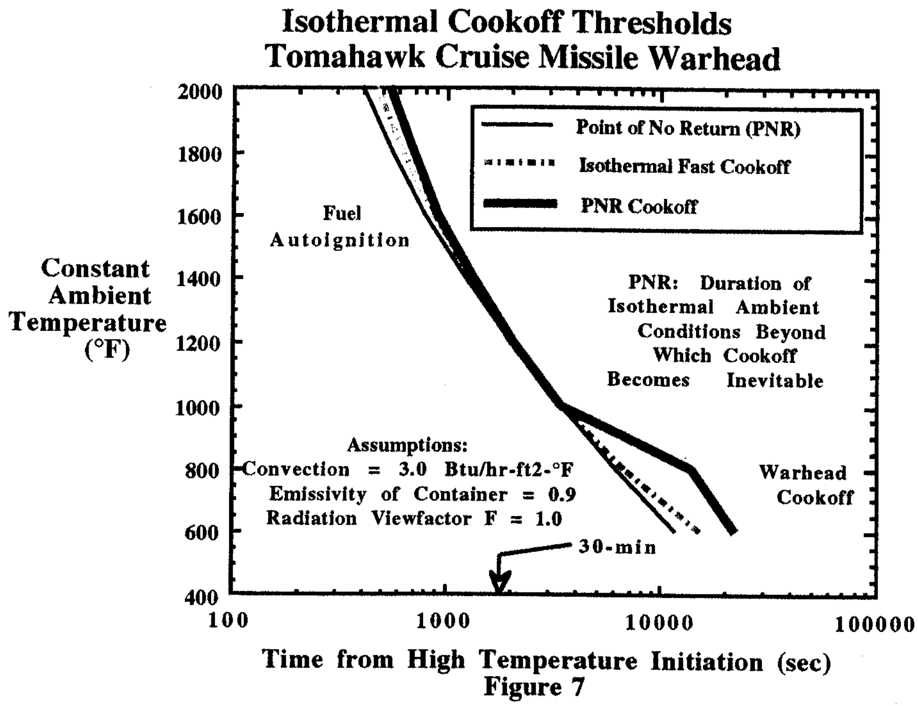

Figure 7 Isothermal Cookoff Thresholds Tomahawk Cruise Missile Warhead

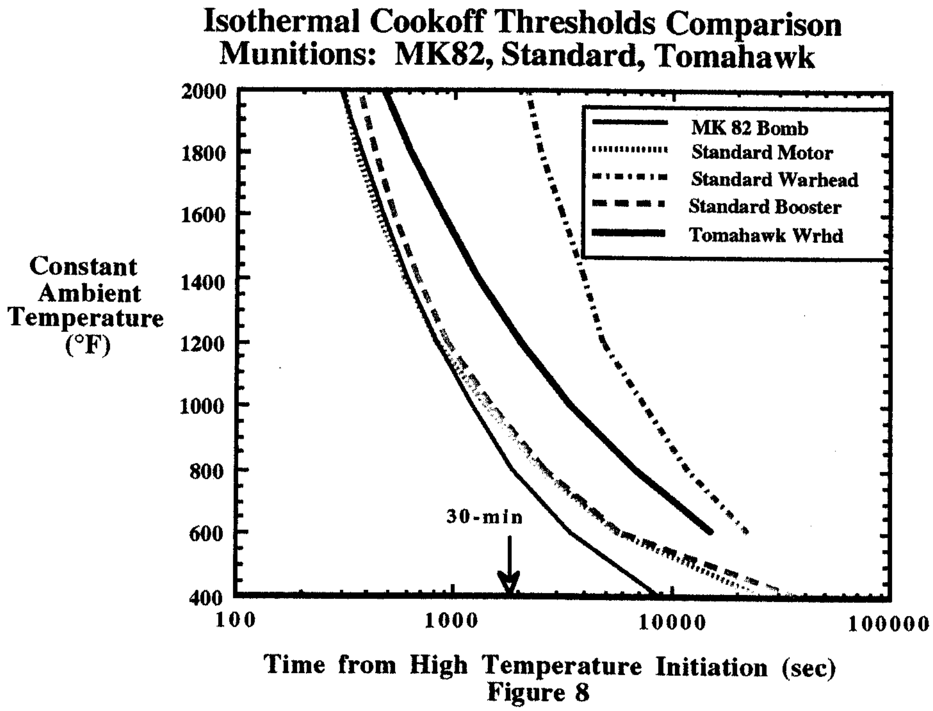

Figure 8 Isothermal Cookoff Thresholds Comparison Munitions: MK82, Standard, Tomahawk

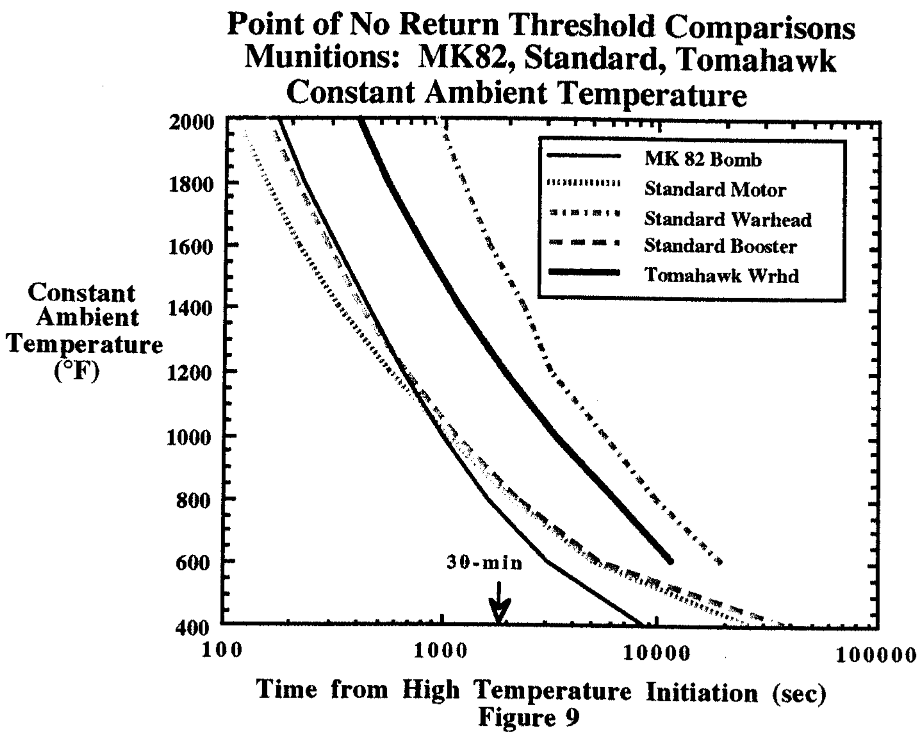

Figure 9 Point of No Return Thresholds Comparison Munitions: MK82, Standard, Tomahawk Contant Ambient Temperature

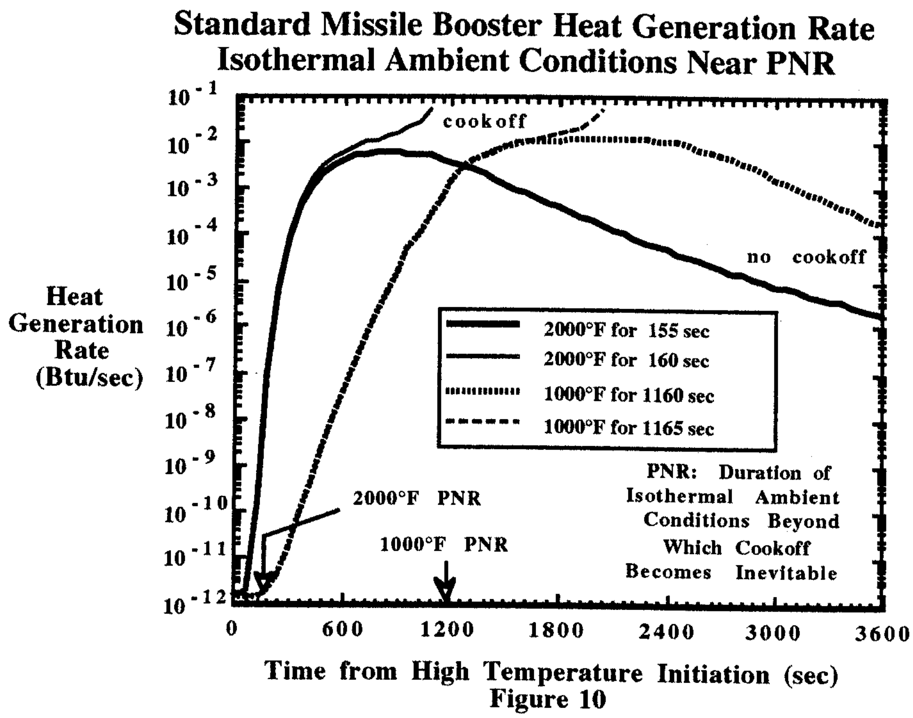

Figure 10 Standard Missile Booster Heat Geneation Rate Isothermal Ambient Conditions Near PNR

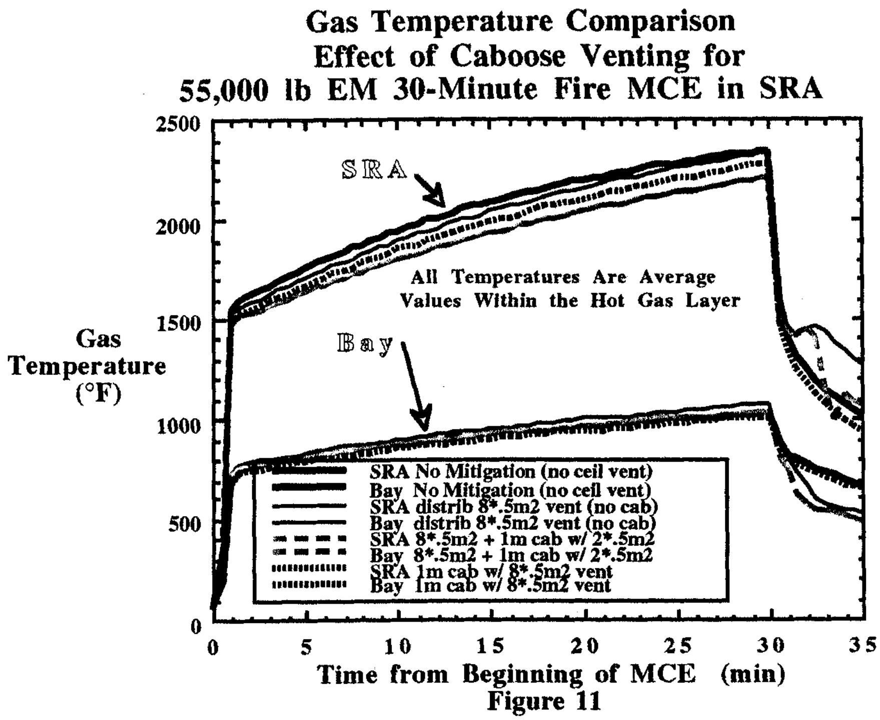

Figure 11 Gas Temperature Comparison Effect of Caboose Venting for 55,000 lb. EM 30-Minute Fire MCE in SRA

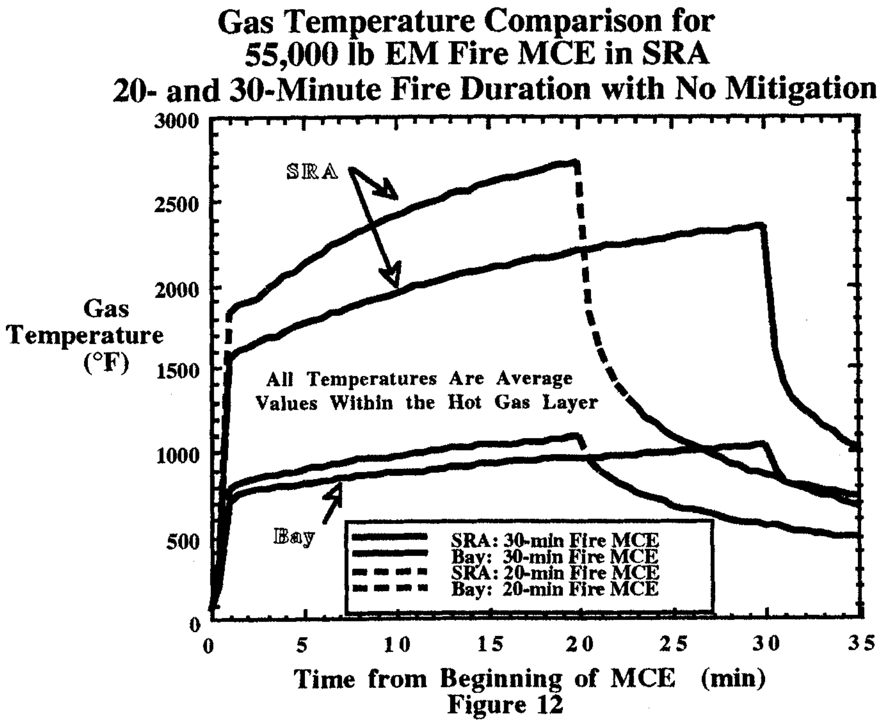

Figure 12 Gas Temperature Comparison for 55,000 lb. EM 30-Minute Fire MCE in SRA 20- and 30- Minute Fire Duration with No Mitigation

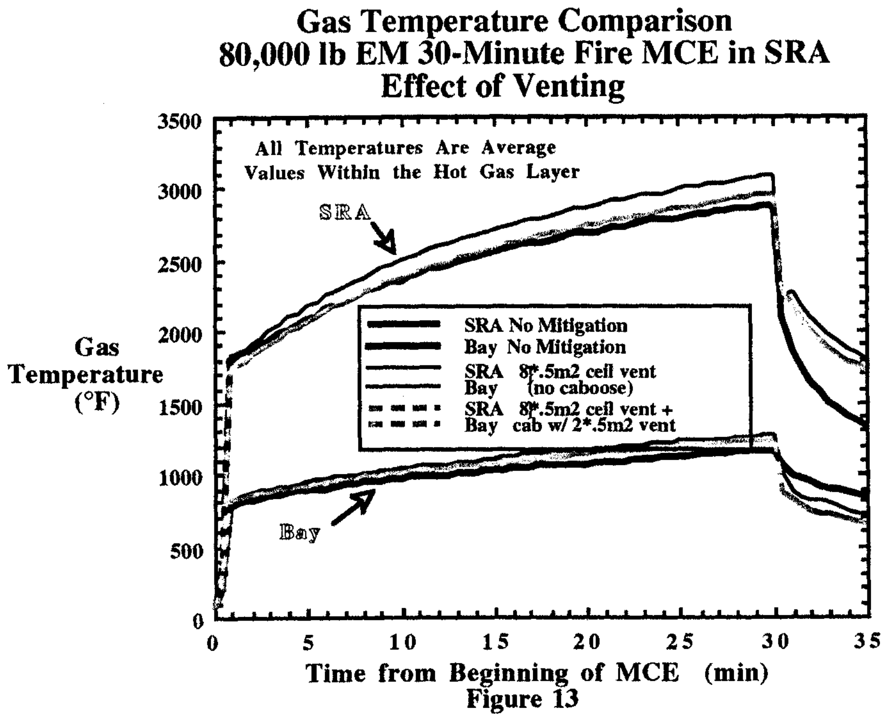

Figure 13 Gas Temperature Comparison
80,000 lb. EM 30-Minute Fire MCE in SRA
Effect of Venting

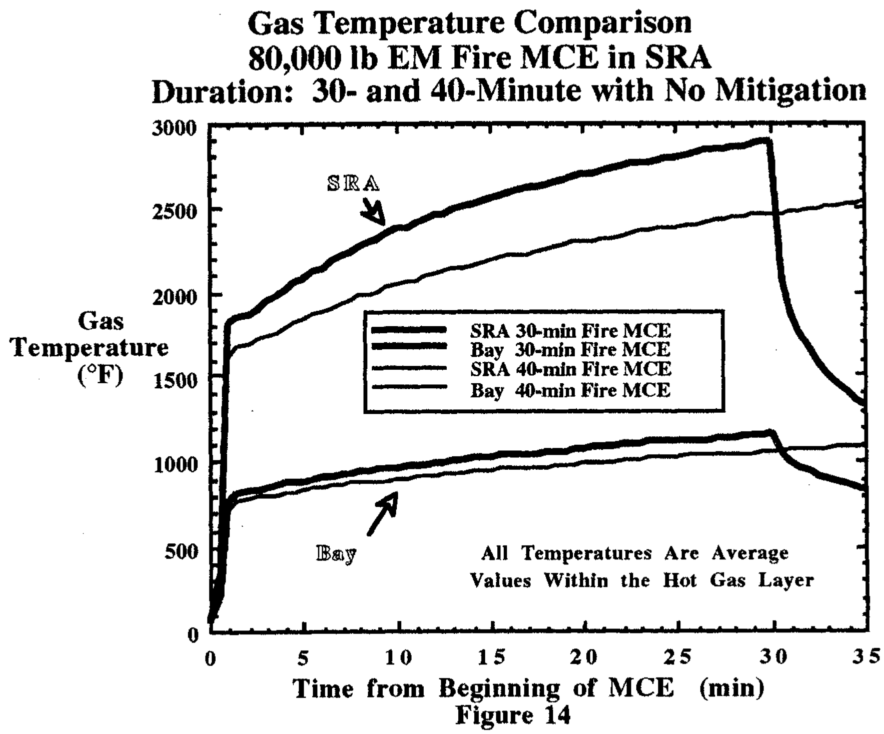

Figure 14 Gas Temperature Comparison
80,000 lb. EM Fire MCE in SRA
Duration: 30- and 40- Minute with No Mitigation

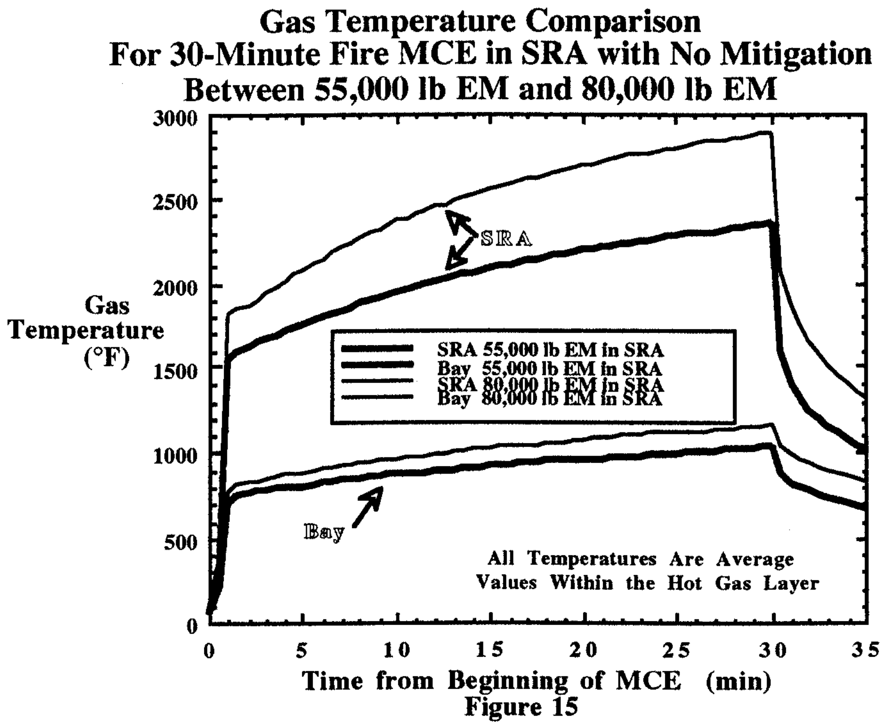

Figure 15 Gas Temperature Comparison
For 30-Minute Fire MCE in SRA with No Mitigation
Between 55,000 lb EM and 80,000 lb EM

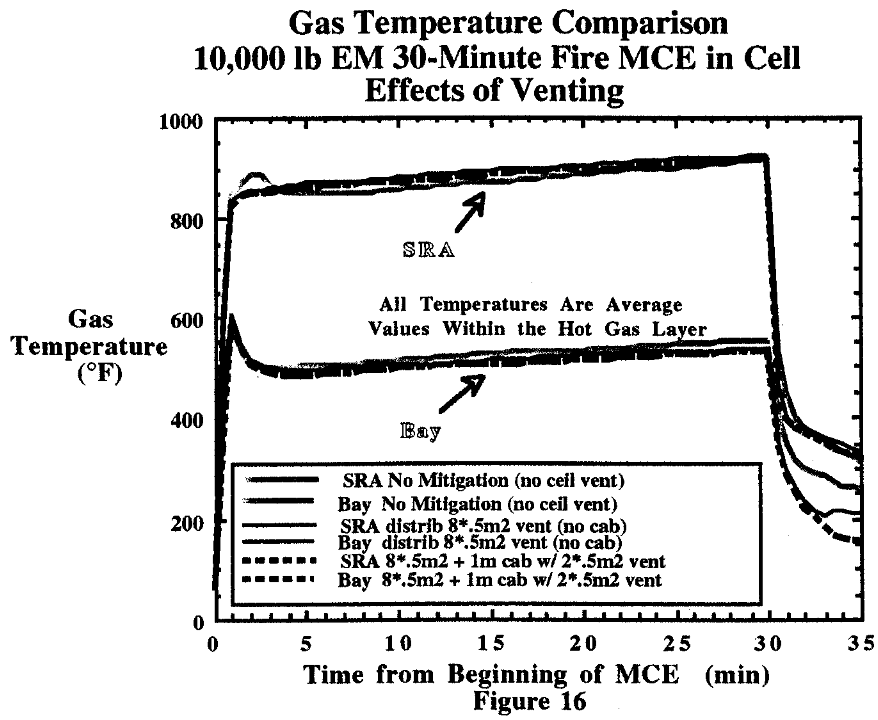

Figure 16 Gas Temperature Comparison 55,000 lb. EM 30-Minute Fire MCE in Cell Effects of Venting

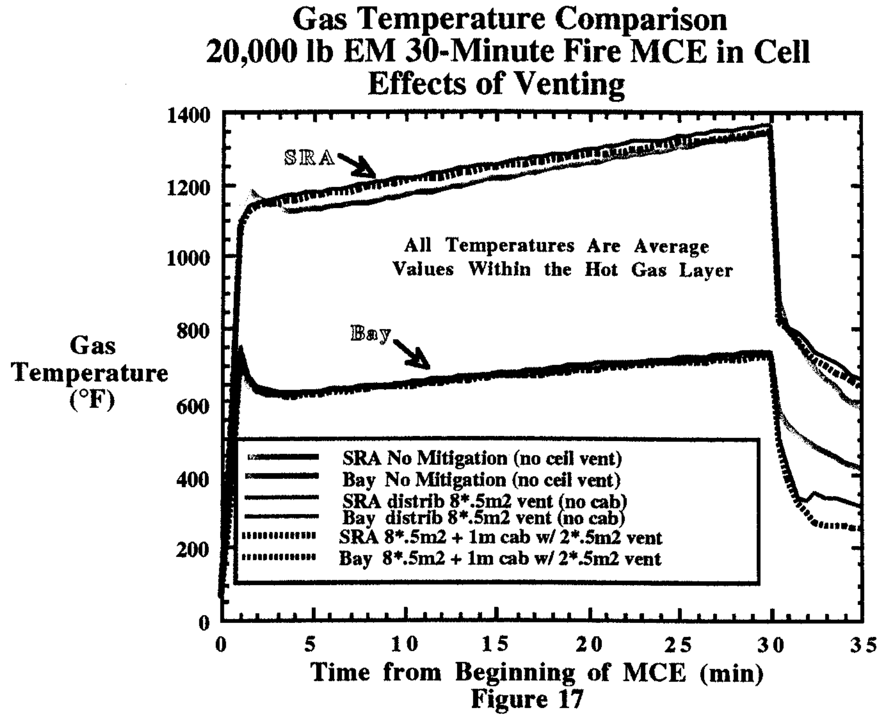

Figure 17 Gas Temperature Comparison
20,000 lb. EM 30-Minute Fire MCE in Cell
Effects of Venting

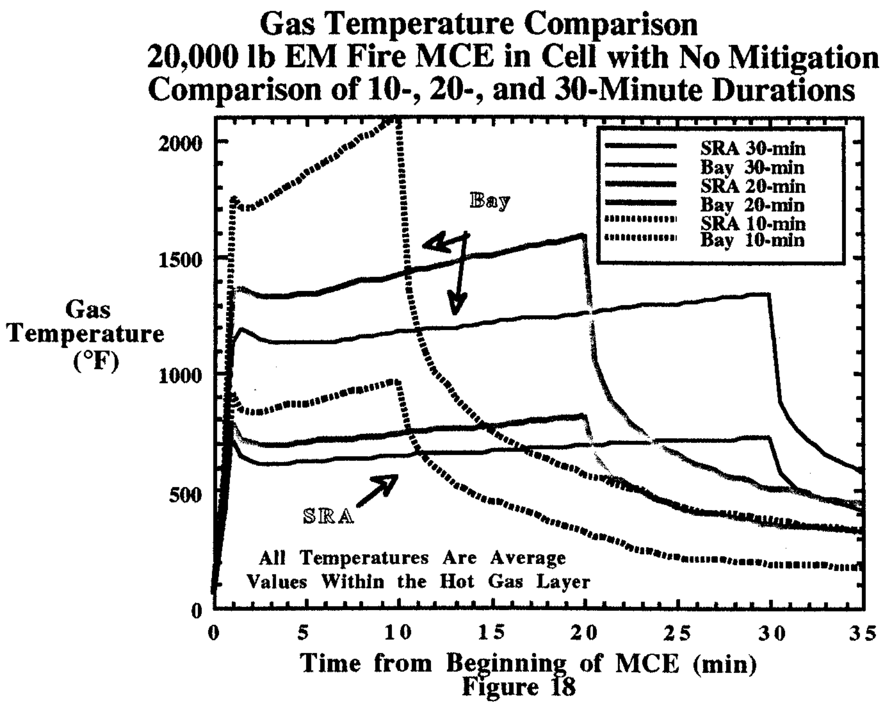

Figure 18 Gas Temperature Comparison
20,000 lb. EM Fire MCE in Cell with No Mitigation
Comparison of 10-, 20-, and 30-Minute Durations

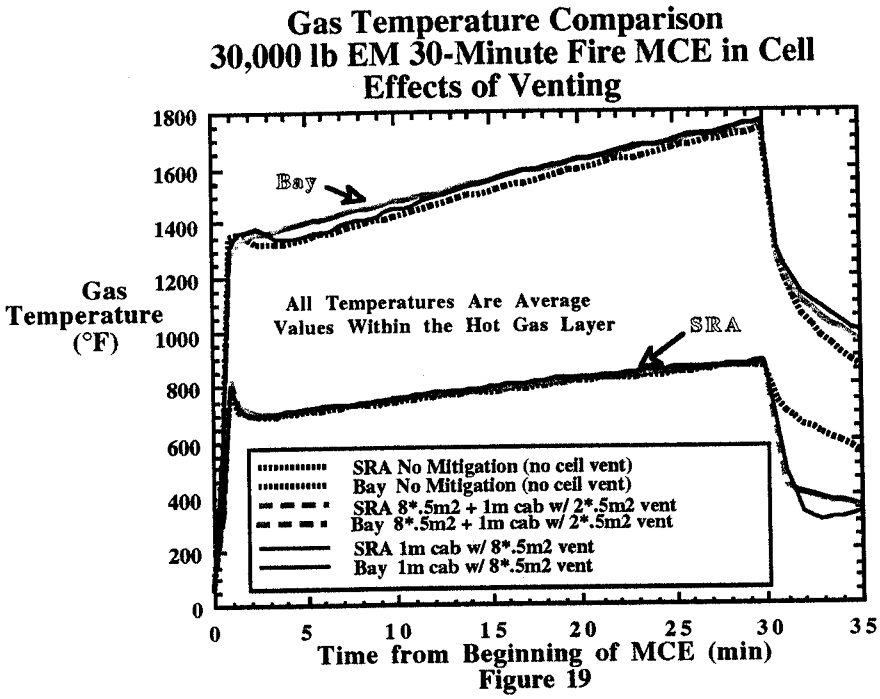

Figure 19 Gas Temperature Comparison 30,000 lb. EM 30-Minute Fire MCE in Cell Effects of Venting

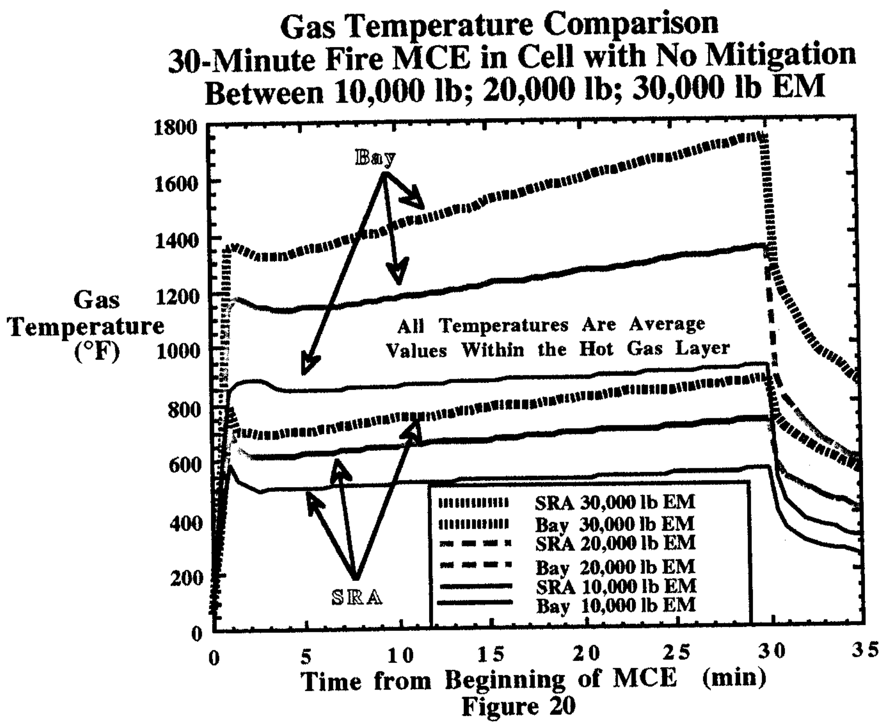

Figure 20 Gas Temperature Comparison
30-Minute Fire MCE in Cell with No Mitigation
Between 10,000 lb; 20,000 lb; 30,000 lb EM

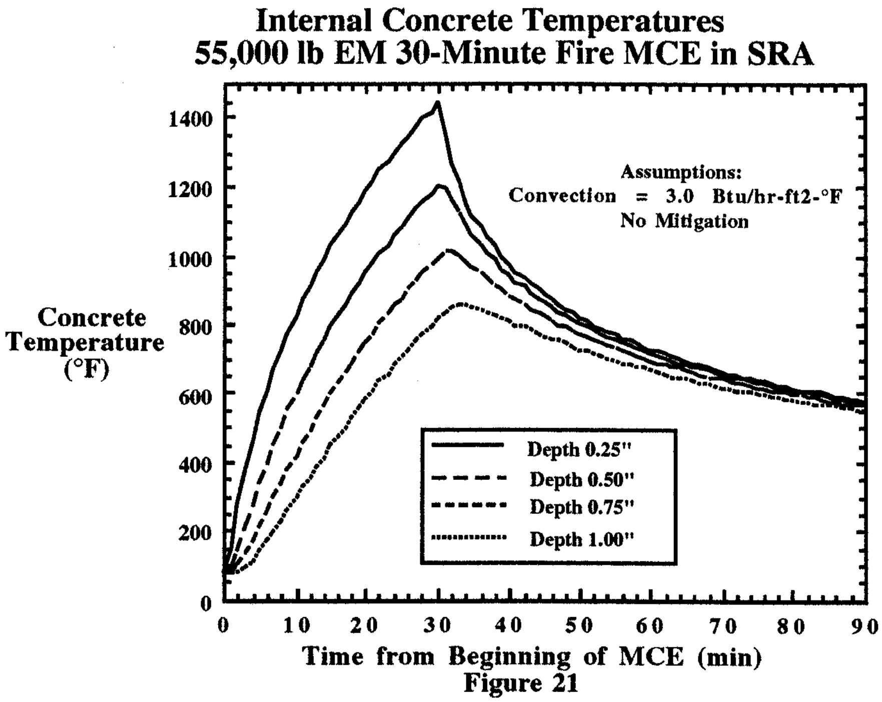

Figure 21 Internal Concrete Temperatures 55,000 lb. EM 30-Minute Fire MCE in SRA

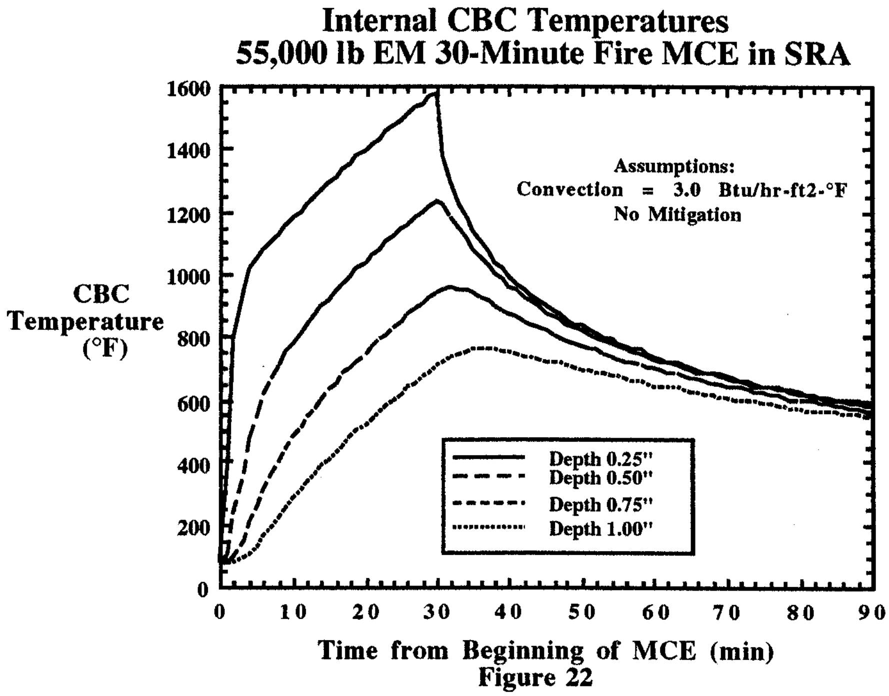

Figure 22 Internal CBC Temperatures
55,000 lb. EM 30-Minute Fire MCE in SRA

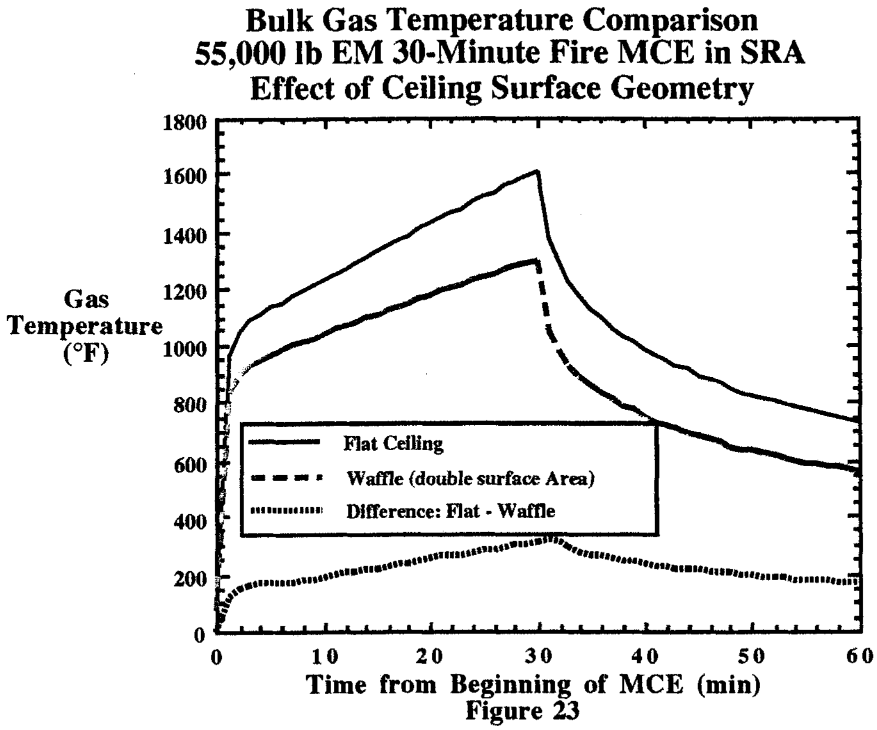

Figure 23 Bulk Temperature Comparison
55,000 lb. EM 30-Minute Fire MCE in SRA
Effect of Ceiling Surface Geometry

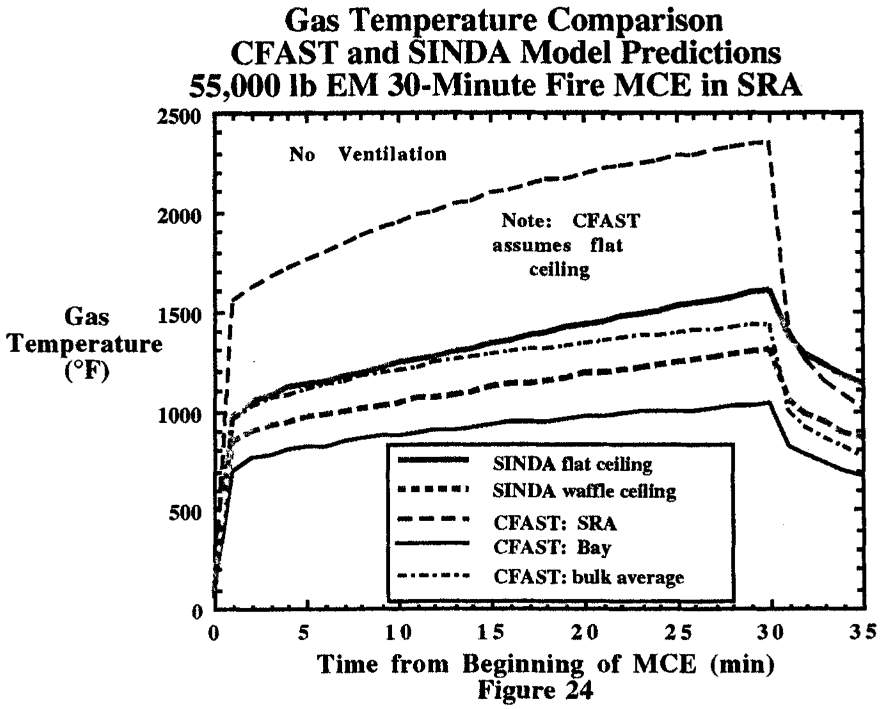

Figure 24 Bulk Temperature Comparison
CFAST and SINDA Model Predictions
55,000 lb. EM 30-Minute Fire MCE in SRA

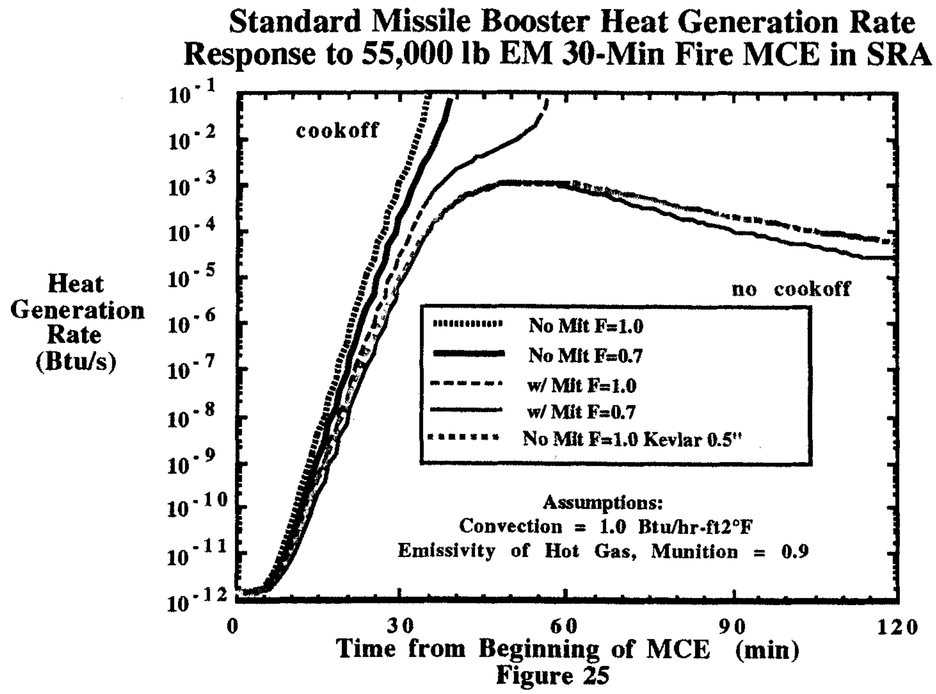

Figure 25 Standard Missile Booster Heat Generation Rate Response to 55,000 lb. EM 30-Minute Fire MCE in SRA

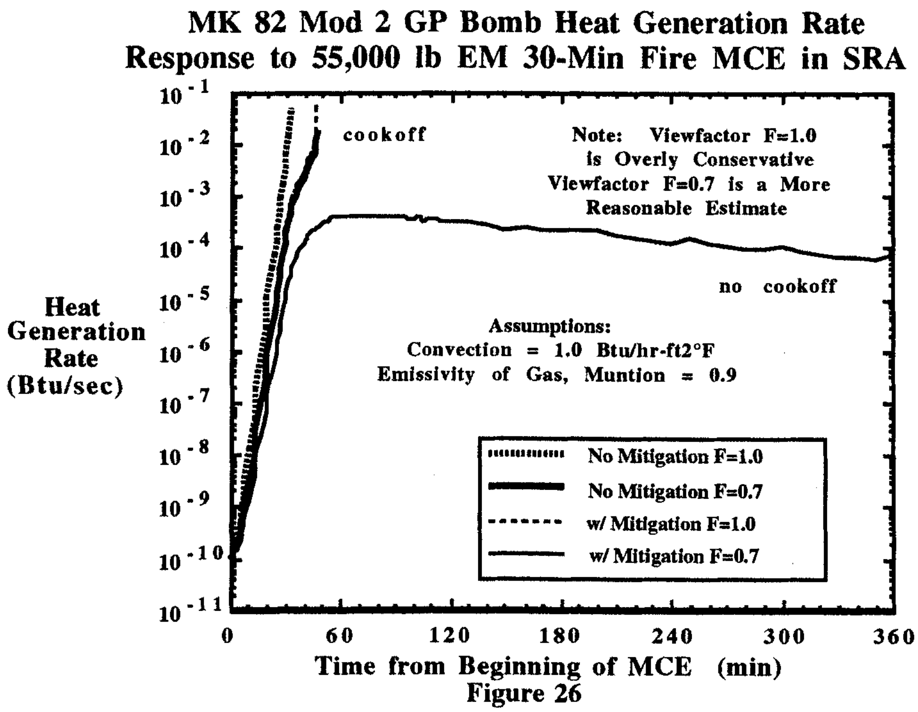

Figure 26 MK 82 Mod 2 GP Bomb Heat Generation Rate Response to 55,000 lb. EM 30-Minute Fire MCE in SRA

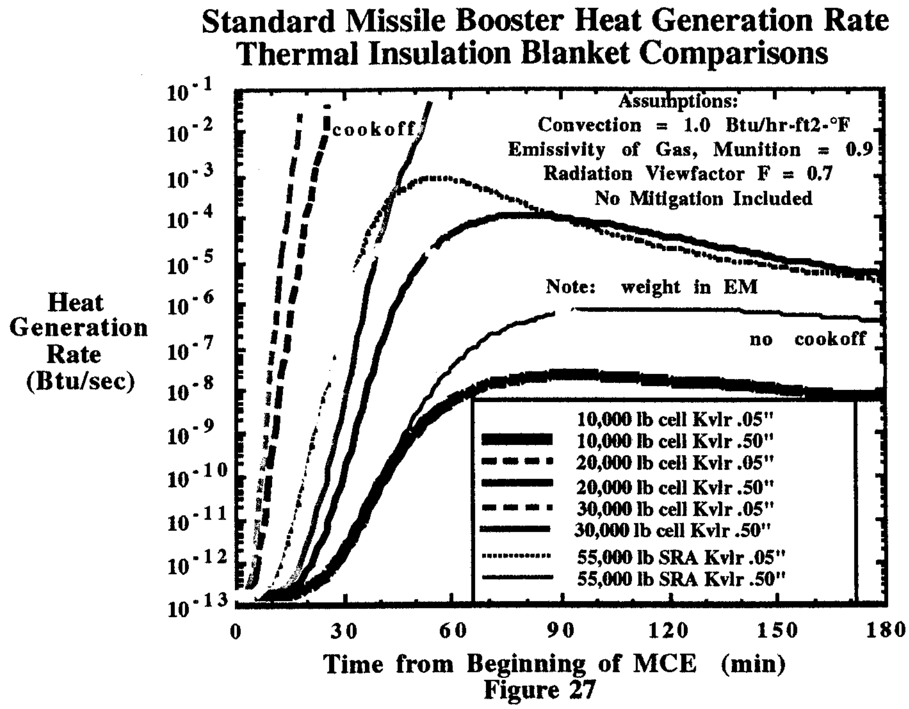

Figure 27 Standard Missile Booster Heat Generation Rate Thermal Insulation Blanket Comparisons

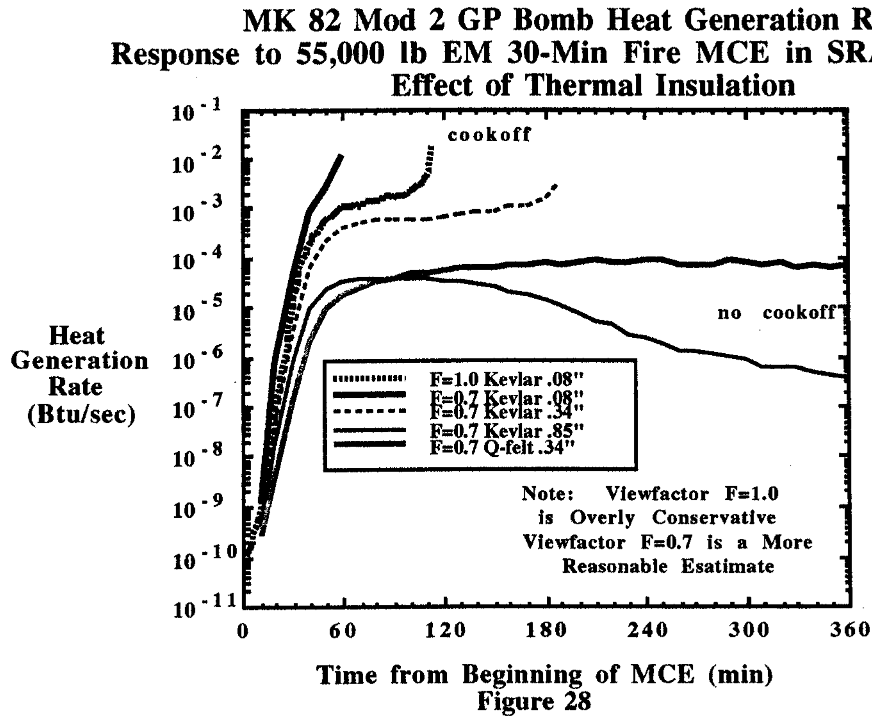

Figure 28 MK 82 Mod 2 GP Bomb Heat Generation Rate Response to 55,000 lb. EM 30-Minute Fire MCE in SRA